

SCIENTIFIC AMERICAN Space & Physics

Plus:

Quasicrystals
discovered

How to make
a wormhole

Relocating Earth
for dummies

The Alien Question

THE LATEST GOVERNMENT REPORT
LACKS ANY BIG REVEALS, BUT
EXPERTS HAVE MIXED FEELINGS

WITH COVERAGE FROM
nature



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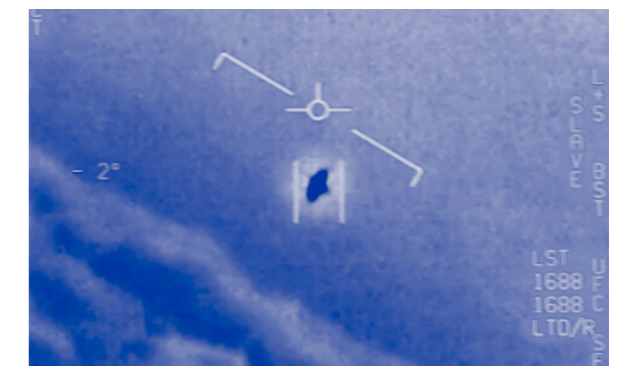
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The Human Framework for Alien Life

A clip from *The Tonight Show* with Johnny Carson in 1978 made the social media rounds in mid-July. The guest that episode—astronomer and science educator Carl Sagan—offered astute criticisms of the then recently released *Star Wars* film for its myopic (and whitewashed) imagining of how organisms from other galaxies might look. In this collection, reporter Leonard David examines the government report published in June that surveys our evidence for extra-terrestrial life so far (see “[Experts Weigh in on Pentagon UFO Report](#)”), and two of our opinion writers contemplate some specific circumstances for alien contact.

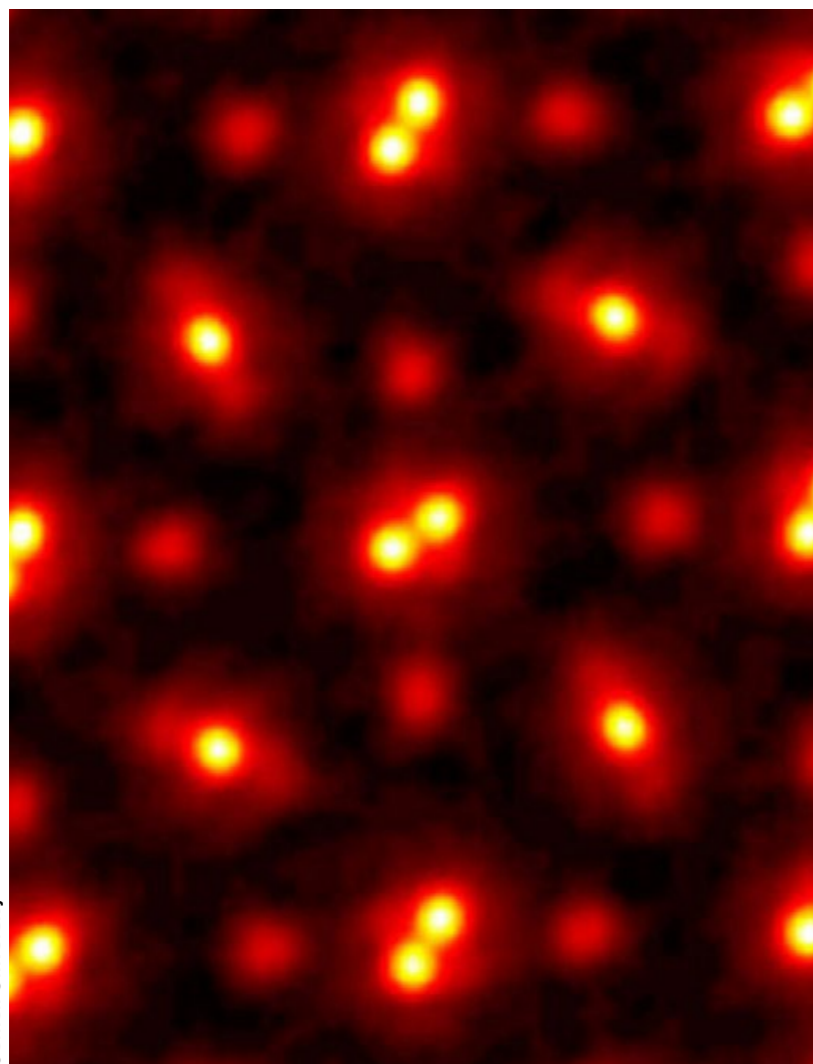
But Sagan’s prescient observations remind me that our search for other life in the universe will always be a strictly human endeavor: how we imagine aliens might look, think or operate and how we look for them or detect their existence—all these factors are based on the human framework of perception. Such limitations will only be problematic if we ignore them and fail to somehow jump beyond the bounds of our minds.

Andrea Gawrylewski
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On the Cover

A still from a video released by the U.S. Department of Defense showing an encounter between a Navy F/A-18 Super Hornet and an unknown object.



Cornell University

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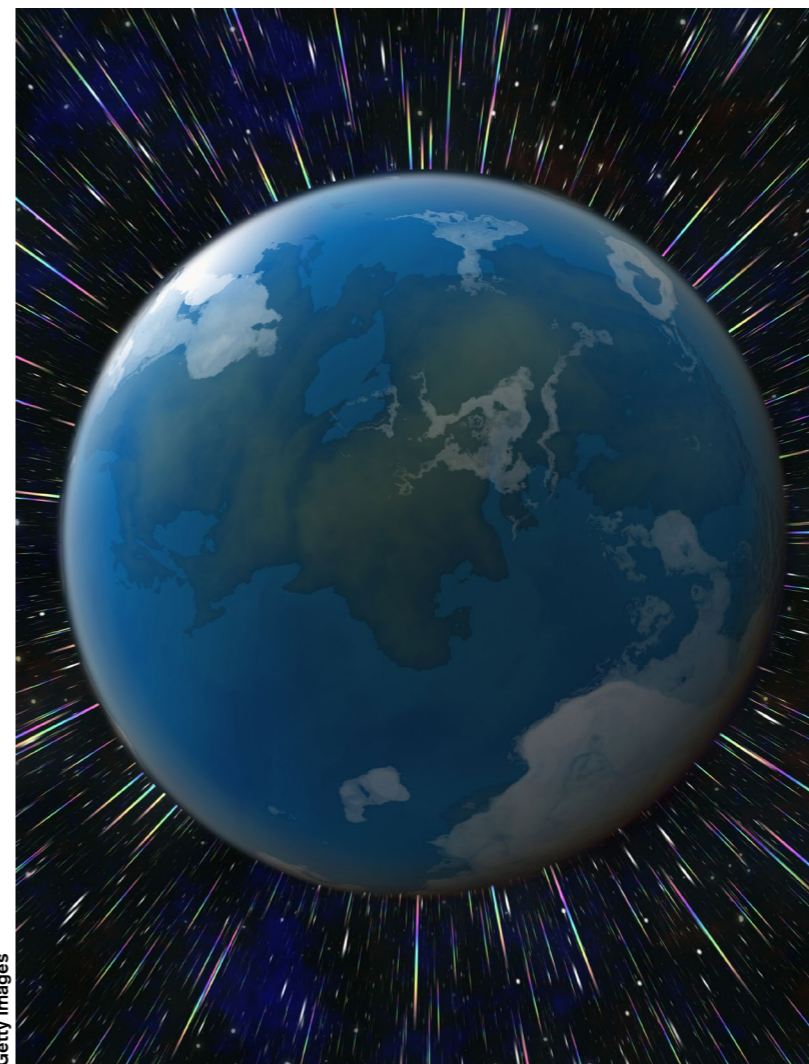
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Getty Images

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First Nuclear Detonation Created “Impossible” Quasicrystals

Their structures were once controversial. Now researchers have discovered quasicrystals in the aftermath of a 1945 bomb test

Scientists searching for quasicrystals—so-called impossible materials with unusual, nonrepeating structures—have identified one in remnants of the world’s first nuclear bomb test.

The previously unknown structure, made of iron, silicon, copper and calcium, probably formed from the fusion of vaporized desert sand and copper cables. Similar materials have been synthesized in the laboratory and identified in meteorites, but this one, described in *Proceedings of the National Acade-*

my of Sciences USA on May 17, is the first example of a quasicrystal with this combination of elements.

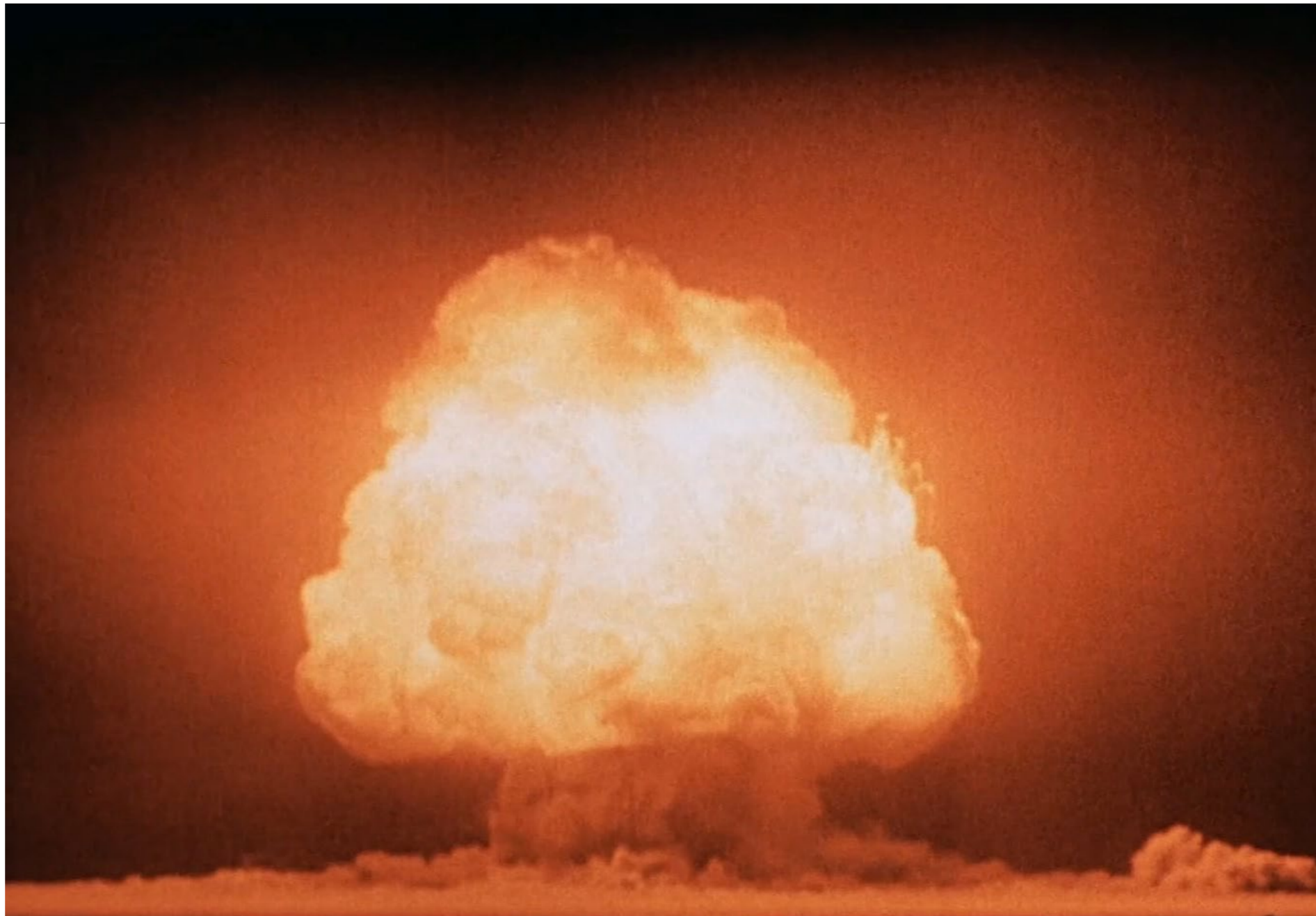
IMPOSSIBLE SYMMETRIES

Quasicrystals contain building blocks of atoms that—unlike those in ordinary crystals—do not repeat in

a regular, brickworklike pattern. Whereas ordinary crystal structures look identical after being translated in certain directions, quasicrystals have symmetries that were once considered impossible: for example, some have pentagonal symmetry and so look the same if rotated by

one fifth of a full twist.

Materials scientist Daniel Shechtman, now at the Technion Israel Institute of Technology in Haifa, first discovered such an impossible symmetry in a synthetic alloy in 1982. It had pentagonal symmetry when rotated in each of various possible



A photograph from the Trinity nuclear test. The explosion fused together vaporized sand and copper wiring to form the mineral trinitite.

directions, something that would occur if its building blocks were icosahedral—that is, had a regular shape with 20 faces. Many researchers initially questioned Shechtman's findings because it is mathematically impossible to fill space using only icosahedrons. Shechtman ultimately won the 2011 Nobel Prize in Chemistry for the discovery.

At around the same time, Paul Steinhardt, a theoretical physicist now at Princeton University, and his collaborators had begun to theorize the possible existence of nonrepeating 3-D structures. These had the same symmetry as an icosahedron but were assembled from building blocks of several different types, which never repeated in the same pattern—thus explaining why the mathematics of symmetrical crystals had missed them. Mathematical physicist Roger Penrose, now at the University of Oxford, and other researchers had previously discovered analogous patterns in two dimensions, which are called Penrose tilings.

Steinhardt recalls the moment in 1982 when he first saw the experimental data from Shechtman's discovery and compared it with his

theoretical predictions. "I stood up from my desk and went and looked at our pattern, and you couldn't tell the difference," he says. "So that was kind of an amazing moment."

In subsequent years, materials scientists synthesized several types of quasicrystal, expanding the range of possible forbidden symmetries. And Steinhardt and his colleagues later found the first naturally occurring "icosahedrite" in fragments from a meteorite recovered on the Kamchatka Peninsula in eastern Siberia. This quasicrystal probably formed in a collision between two asteroids in the early solar system, Steinhardt says. Some of the laboratory-made quasicrystals were also produced by smashing materials together at high speed, so Steinhardt and his team wondered whether the shockwaves from nuclear explosions might form quasicrystals, too.

"SLICING AND DICING"

In the aftermath of the Trinity test—the first-ever detonation of a nuclear bomb, which took place on July 16, 1945, at New Mexico's Alamogordo Bombing Range—researchers found a vast field of

greenish glassy material that had formed from the liquefaction of desert sand. They dubbed this trinitite.

The plutonium bomb had been detonated on top of a 30-meter-high tower, which was laden with sensors and their cables. As a result, some of the trinitite that formed had reddish inclusions, Steinhardt says. "It was a fusion of natural material with copper from the transmission lines." Quasicrystals often form from elements that would not normally combine, so Steinhardt and his colleagues thought samples of the red trinitite would be a good place to look for quasicrystals.

"Over the course of 10 months we were slicing and dicing, looking at all sorts of minerals," Steinhardt says. "Finally, we found a tiny grain." The quasicrystal has the same kind of icosahedral symmetry as the one in Shechtman's original discovery.

"The dominance of silicon in its structure is quite distinct," says Valeria Molinero, a theoretical chemist at the University of Utah. "However, after many quasicrystals have been synthesized in the lab," she says, "what I find truly intriguing is that they are so scarce in nature."

Steinhardt says this might be because the formation of quasicrystals involves "unusual combinations of elements and unusual arrangements."

Like most known quasicrystals, the trinitite structure seems to be an alloy—a metal-like material made up of positive ions in a sea of electrons. This is unusual for silicon, which typically occurs in rock in an oxidized form: reversing the oxidation would require extreme conditions, such as the intense heat and pressure of a shockwave, says Lincoln Hollister, a geoscientist at Princeton.

Steinhardt suggests that quasicrystals could be used for a kind of nuclear forensic science because they might reveal sites where a covert nuclear test has occurred. Quasicrystals might also form in other materials that were generated in violent conditions, such as fulgurite, the material made when lightning strikes rock, sand or other sediments. "The quasicrystal saga will continue!" Hollister says.

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—Davide Castelvechi

Stars Made of Antimatter Might Be Lurking in the Universe

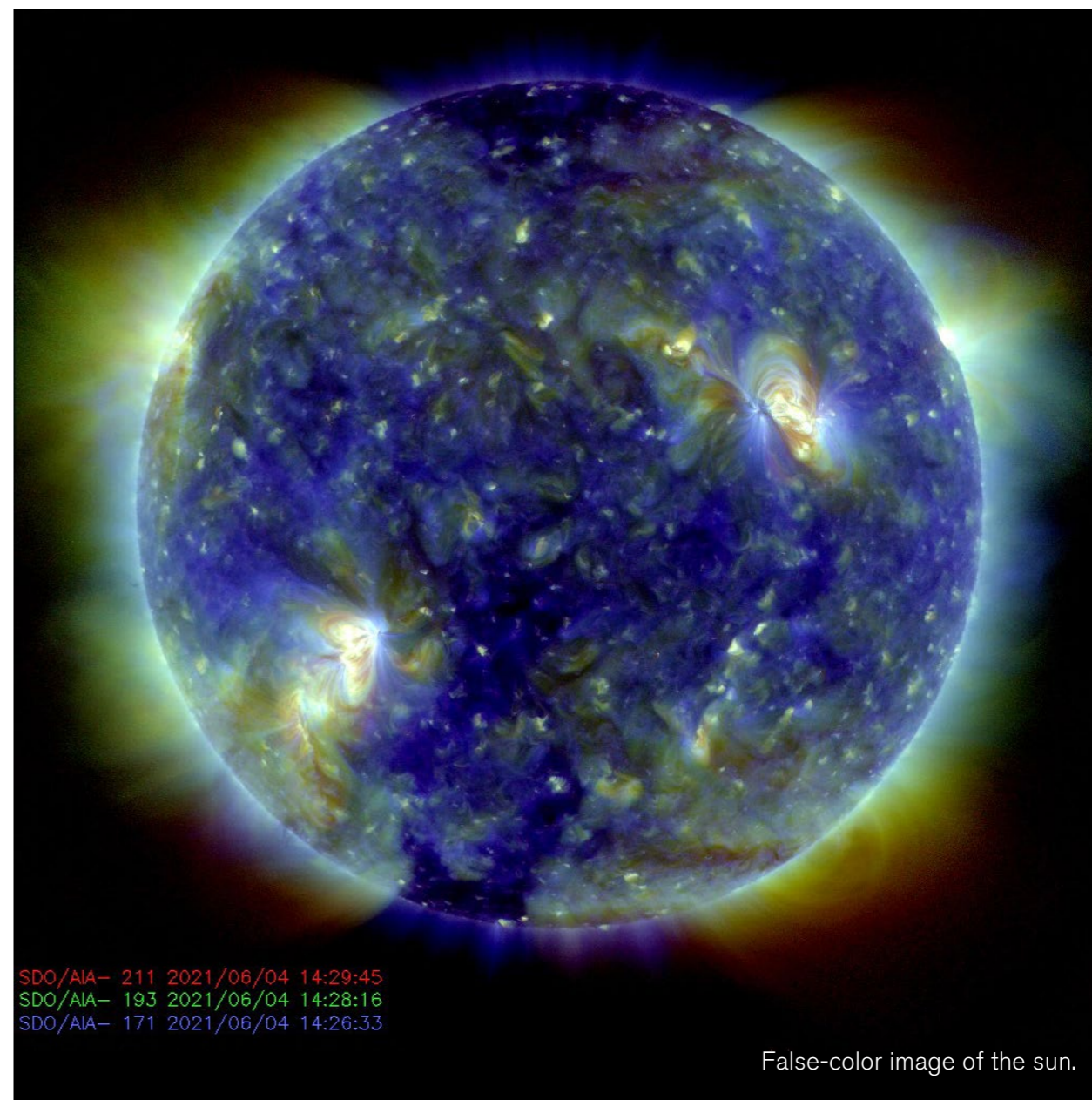
Circumstantial evidence could point to a mind-blowing solution to an antimatter mystery—or to the need for better space-based particle physics experiments

Antimatter may seem like the stuff of science fiction—especially because scarcely any of it can be seen in our universe, despite physicists' best theories suggesting antimatter should have arisen in equal proportion to normal matter during the big bang. But researchers do regularly produce particles of antimatter in their experiments, and they have the inklings of an explanation for its cosmic absence: Whenever antimatter and normal matter meet, they mutually annihilate in a burst of energy. The slimmest overabundance of normal matter at the beginning of time would have therefore effectively wiped antimatter off the celestial map, save for its occasional production in cosmic-

ray strikes, human-made particle accelerators and perhaps certain theorized interactions between particles of dark matter.

That is why physicists were so greatly puzzled back in 2018, when the head of the Alpha Magnetic Spectrometer (AMS) experiment mounted on the exterior of the International Space Station announced that the instrument might have detected two antihelium nuclei—in addition to six that were possibly detected earlier. Any way you slice it, known natural processes would struggle to produce enough antihelium for any of it to end up in our space-based detectors. But the easiest of all those hard methods would be to cook up the antihelium inside antistars—which, of course, do not seem to exist. Despite the fact that the entirely unexpected AMS results have yet to be confirmed, let alone formally published, scientists have taken them seriously, and some have scrambled to find explanations.

Inspired by the tentative AMS findings, a group of researchers recently published a study calculating the maximum number of antimatter stars that could be lurking in our universe, based on



a count of currently unexplained gamma-ray sources found by the Fermi Large Area Telescope (LAT). Simon Dupourqué, the study's lead author and an astrophysics graduate

student at the Research Institute in Astrophysics and Planetology at the University of Toulouse III—Paul Sabatier in France and the French National Center for Scientific

Research (CNRS), made the estimate after looking for antistar candidates in a decade's worth of the LAT's data.

Antistars would shine much as normal ones do—producing light of the same wavelengths. But they would exist in a matter-dominated universe. As particles and gases made of regular matter fell into such a star's gravitational pull and made contact with its antimatter, the resulting annihilation would produce a flash of high-energy light. We can see this light as a specific color of gamma rays. The team took 10 years of data, which amounted to roughly 6,000 light-emitting objects. They pared the list down to sources that shone with the right gamma frequency and that were not ascribed to previously cataloged astronomical objects. "So this left us with 14 candidates, which, in my opinion and my co-authors' opinion, too, are not antistars," Dupourqué says. If all of those sources were such stars, however, the group estimated that about one antistar would exist for every 400,000 ordinary ones in our stellar neck of the woods.

In place of any putative antistars, Dupourqué says, these gamma

flashes could instead be coming from pulsars or the supermassive black holes at the centers of galaxies. Or they might simply be some kind of detector noise. The next step would be to point telescopes at the locations of the 14 candidate sources to find out if they resemble a star or a prosaic gamma-emitting object.

Given some interesting but questionable gamma sources, calculating the conceivable "upper limit" to the number of antistars is a long shot from actually discovering such astrophysical objects. So most researchers are not leaning toward that conclusion. "According to both theory and observations of extragalactic gamma rays, there should be no antistars in our galaxy.... One would only expect upper limits consistent with zero," says Floyd Stecker, an astrophysicist at NASA's Goddard Space Flight Center, who was not involved in the research. "However, it is always good to have further observational data confirming this."

If scientists, including the authors, are skeptical of antistars' very existence, why are they worth discussing? The mystery lies in those pesky possible detections of antihelium made by the AMS, which

"According to both theory and observations of extragalactic gamma rays, there should be no antistars in our galaxy.... One would only expect upper limits consistent with zero."

—Floyd Stecker

remain unexplained. Antiparticles can be created from two known natural sources—cosmic rays and dark matter—but the odds that either of them are responsible appear to be vanishingly slim.

As we increase the size of an atom, it becomes harder and harder to produce as an antiparticle, says Vivian Poulin, a CNRS cosmologist based in Montpellier, France. This "means that it's rarer and rarer that it occurs, but it's allowed by physics." An antiproton is relatively easy to form, yet anything heavier, such as antideuterium—an antiproton plus an antineutron—or antihelium—two antiprotons plus typically one or two antineutrons—gets progressively harder to make as it gets more massive. In a paper published in 2019, Poulin used the AMS's potential antihelium detections to calculate a rough estimate of the prevalence of antistars, which

inspired Dupourqué's new study.

In a process called spallation, high-energy cosmic rays from exploding stars can ram into interstellar gas particles, says Pierre Salati, a particle astrophysicist at the Annecy-le-Vieux Particle Physics Laboratory, who worked on Poulin's 2019 study. The team responsible for the AMS's antiparticle detections claim it may have detected six antihelium 3 nuclei, which would be incredibly rare products of spallation, and two antihelium 4 nuclei, which would be almost statistically impossible to form from cosmic rays, Salati says. (The difference between the two isotopes is the addition of one antineutron.)

As for dark matter, certain models predict that dark matter particles can annihilate one another—a process that could also create antiparticles. But this process still might not be able to make antihelium 4 in high enough quantities for us to have a

realistic chance of ever seeing it (if such speculative models reflect reality at all). That is why the antistar hypothesis is still on the table. Verified antihelium detections would be a good indicator for the existence of antistars, but so far the AMS is the lone experiment to offer any such evidence—which has yet to be granted peer-reviewed publication, Salati notes.

“It’s a very challenging analysis because, for every one antihelium event, there are 100 million regular helium events,” says Ilias Cholis, an astrophysicist at Oakland University, who also worked on Poulin’s study. It is possible, he and others say, that the detections turn out to be a fluke of a very complicated analysis.

Samuel Ting, a Nobel laureate physicist at the Massachusetts Institute of Technology, heads the AMS team and first publicly presented the two latest possible antihelium detections—the antihelium 4 candidates—in 2018. “We are not yet ready to publish any heavy antimatter results,” he says. “We are collecting more data before any [further] announcement is made.”

It is possible that a different experiment may give answers sooner.

The General AntiParticle Spectrometer (GAPS) experiment is a balloon-borne detector that will hunt for antiparticles above Antarctica this year. Finding more antiparticles—antideuterons or even antihelium, in particular, according to Cholis—with the GAPS detector would make the AMS results far more convincing.

If antistars were found to be the culprit, that discovery would require a major reenvisioning of the universe’s evolution: no longer could we relegate antistars and other hypothetical astrophysical objects composed of antimatter to the fringes of reasonable speculation. Even if they do exist, however, antistars probably are not forming now, Salati says, because their presumptive natal clouds of antihydrogen would face steep odds of avoiding annihilation for the past 13 billion years or so. Thus, any antistars that might be found likely would be exceedingly old remnants of the early universe. If so, one deep mystery would be replaced with another: How, exactly, did such ancient relics manage to survive to today? As is often the case, a new discovery raises far more questions than it answers.

—*Leto Sapunar*

Wormhole Tunnels in Spacetime May Be Possible, New Research Suggests

There may be realistic ways to create cosmic bridges predicted by general relativity

In the early days of research on black holes, before they even had that name, physicists did not yet know if these bizarre objects existed in the real world. They might have been a quirk of the complicated math used in the then still young general theory of relativity, which describes gravity. Over the years, though, evidence has accumulated that black holes are very real and even exist right here in our galaxy.

Today another strange prediction from general relativity—wormholes, those fantastical-sounding tunnels to the other side of the universe—hang in the same sort of balance. Are they real? And if they are out there in our cosmos, could humans hope to use them for getting around? After their prediction in 1935, research seemed to point toward no—wormholes

appeared unlikely to be an element of reality. But new work offers hints of how they could arise, and the process may be easier than physicists have long thought.

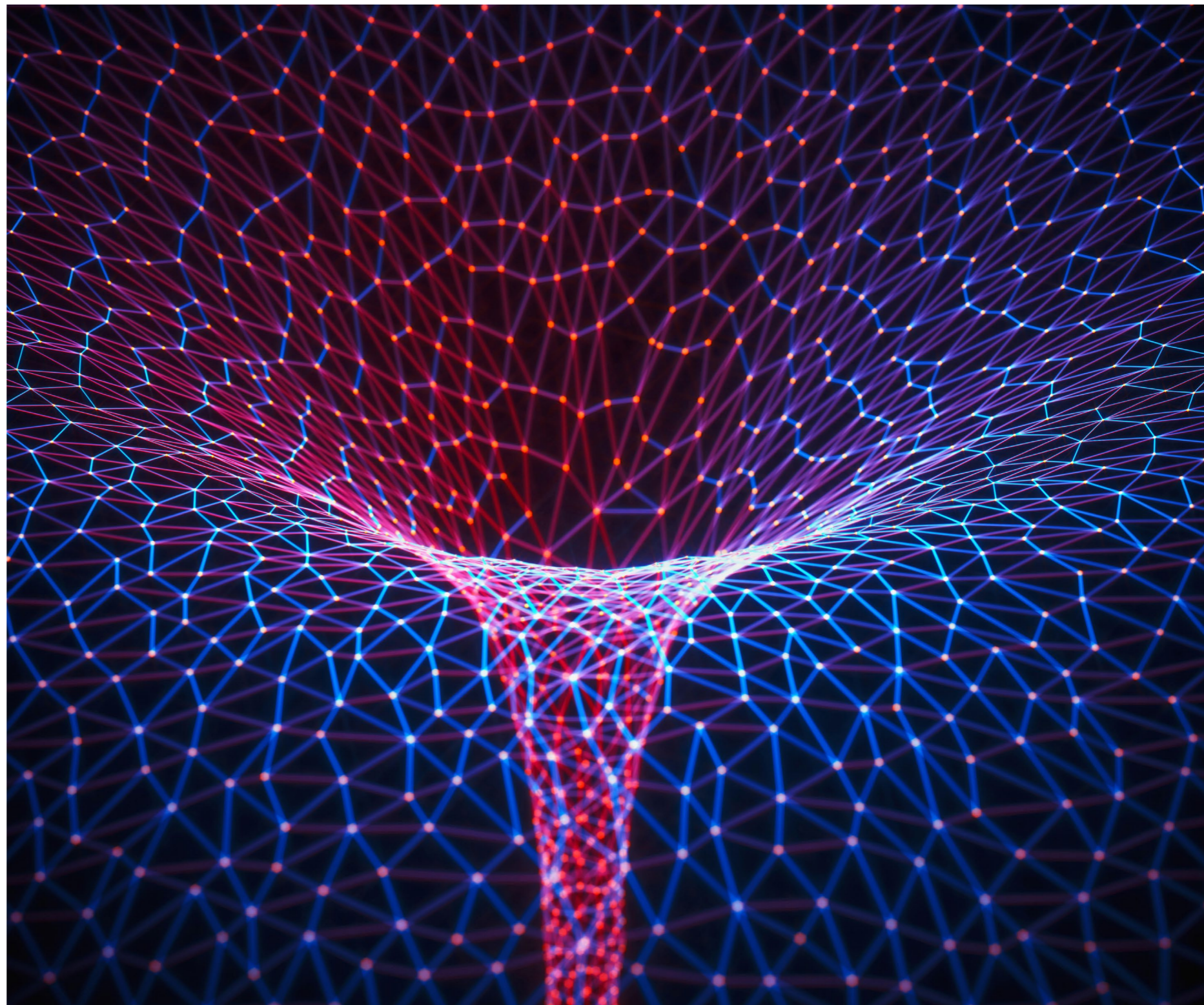
The original idea of a wormhole came from physicists Albert Einstein and Nathan Rosen. They studied the strange equations that we now know describe that unescapable pocket of space we call a black hole and asked what they really represented. Einstein and Rosen discovered that, theoretically at least, a black hole’s surface might work as a bridge that connected to a second patch of space. The journey might be as if you went down the drain of your bathtub, and instead of getting stuck in the pipes, you came out into another tub just like the first.

Subsequent work expanded this idea but turned up two persistent challenges that prevent the formation of easily spotted, humanly usable wormholes: fragility and tininess. First, it turns out that in general relativity, the gravitational attraction of any normal matter passing through a wormhole acts to pull the tunnel shut. Making a stable wormhole requires some kind of extra, atypical ingredient that acts

to keep the hole open, which researchers call “exotic” matter.

Second, the kinds of wormhole-creating processes that scientists had studied rely on effects that could prevent a macroscopic traveler from entering. The challenge is that the process that creates the wormhole and the exotic matter that stabilizes it cannot stray too far from familiar physics. “Exotic” does not mean physicists can dream up any sort of stuff that gets the job done on paper. But so far familiar physics has delivered only microscopic wormholes. A bigger wormhole seems to require a process or type of matter that is both unusual and believable. “That’s the delicacy,” says Brianna Grado-White, a physicist and wormhole researcher at Brandeis University.

A breakthrough occurred in late 2017, when physicists Ping Gao and Daniel Jafferis, both then at Harvard University, and Aron Wall, then at the Institute for Advanced Study in Princeton, N.J., discovered a way to prop open wormholes with quantum entanglement—a kind of long-distance connection between quantum entities. The peculiar nature of entanglement allows it to provide the exotic ingredient needed for wormhole stability. And



because entanglement is a standard feature of quantum physics, it is relatively easy to create. “It’s really a beautiful theoretical idea,” says Nabil Iqbal, a physicist at Durham University in England, who was not involved in the research. Though the method helps to stabilize wormholes, it can still deliver only microscopic ones. But this new approach has inspired a stream of work that uses the entanglement trick with different sorts of matter in the hopes of bigger, longer-lasting holes.

One easy-to-picture idea comes from a preprint study by Iqbal and his Durham colleague Simon Ross. The two tried to see if they could make the Gao-Jafferis-Wall method produce a large wormhole. “We thought it would be interesting, from a sci-fi point of view, to push the limits and see whether this thing could exist,” Iqbal says. Their work showed how special disturbances within the magnetic fields surrounding a black hole could, in theory, generate stable wormholes. Unfortunately, the effect still only forms microscopic wormholes, and Iqbal says it is highly unlikely the situation would occur in reality.

Iqbal and Ross’s work highlights the delicate part of wormhole

construction: finding a realistic process that does not require something added from way beyond the bounds of familiar physics. Physicist Juan Maldacena of the Institute for Advanced Study, who had suggested connections between wormholes and entanglement back in 2013, and his collaborator Alexey Milekhin of Princeton University have found a method that could produce large holes. The catch in their approach is that the mysterious dark matter that fills our universe must behave in a particular way, and we may not live in a universe anything like this. “We have a limited toolbox,” Grado-White says. “To get something to look the way we need it, there’s only so many things we can do with that toolbox.”

The boom in wormhole research continues. So far nothing like a made-to-order human-sized wormhole machine looks likely, but the results do show progress. “We’re learning that we can, in fact, build wormholes that stay open using simple quantum effects,” Grado-White says. “For a very long time, we didn’t think these things were possible to build—it turns out that we can.”

—Brendan Z. Foster

The Top Unsolved Questions in Mathematics Remain Mostly Mysterious

Just one of the seven Millennium Prize Problems named 21 years ago has been solved

Twenty-one years ago mathematicians released a list of the top seven unsolved problems in the field. Answering them would offer major new insights in fundamental mathematics and might even have real-world consequences for technologies such as cryptography.

But big questions in math have not often attracted the same level of outside interest that mysteries in other scientific areas have. When it comes to understanding what math research looks like or what the point of it is, many folks are still stumped, says Wei Ho, a mathematician at the University of Michigan. Although people often misunderstand the nature of her work, Ho says it does not have to be difficult to explain. “My cocktail party spiel is

always about elliptic curves,” she adds. Ho often asks partygoers, “You know middle school parabolas and circles? Once you start making a cubic equation, things get really hard.... There are so many open questions about them.”

One famous open problem called the Birch and Swinnerton-Dyer conjecture concerns the nature of solutions to equations of elliptic curves, and it is one of the seven Millennium Prize Problems that were selected by the founding scientific advisory board of the Clay Mathematics Institute (CMI) as what the institute describes as “some of the most difficult problems with which mathematicians were grappling at the turn of the second millennium.” At a special event held in Paris on May 24, 2000, the institute announced a prize of \$1 million for each solution or counterexample that would effectively resolve one of these problems for the first time. Rules revised in 2018 stipulate that the result must achieve “general acceptance in the global mathematics community.”

The 2000 proclamation gave \$7 million worth of reasons for people to work on the seven prob-

lems: the Riemann hypothesis, the Birch and Swinnerton-Dyer conjecture, the P versus NP problem, the Yang-Mills existence and mass gap problem, the Poincaré conjecture, the Navier-Stokes existence and smoothness problem, and the Hodge conjecture. Yet despite the fanfare and monetary incentive, after 21 years, only the Poincaré conjecture has been solved.

AN UNEXPECTED SOLUTION

In 2002 and 2003 Grigori Perelman, a Russian mathematician then at the St. Petersburg Department of the Steklov Mathematical Institute of the Russian Academy of Sciences, shared work connected to his solution of the Poincaré conjecture online. In 2010 CMI announced that Perelman had proved the conjecture and, along the way, had also solved the late mathematician William Thurston's related geometrization conjecture. (Perelman, who rarely engages with the public, famously turned down the prize money.)

According to CMI, the Poincaré conjecture focuses on a topological question about whether spheres with three-dimensional surfaces are “essentially characterized” by a

property called “simple connectivity.” That property means that if you encase the surface of the sphere with a rubber band, you can compress that band—without tearing it or removing it from the surface—until it is just a single point. A two-dimensional sphere or doughnut hole is simply connected, but a doughnut (or another shape with a hole in it) is not.

Martin Bridson, a mathematician at the University of Oxford and president of CMI, describes Perelman's proof as “one of the great events of, certainly, the past 20 years” and “a crowning achievement of many strands of thought and our understanding of what three-dimensional spaces are like.” And the discovery could lead to even more insights in the future. “The proof required new tools, which are themselves giving far-reaching applications in mathematics and physics,” says Ken Ono, a mathematician at the University of Virginia.

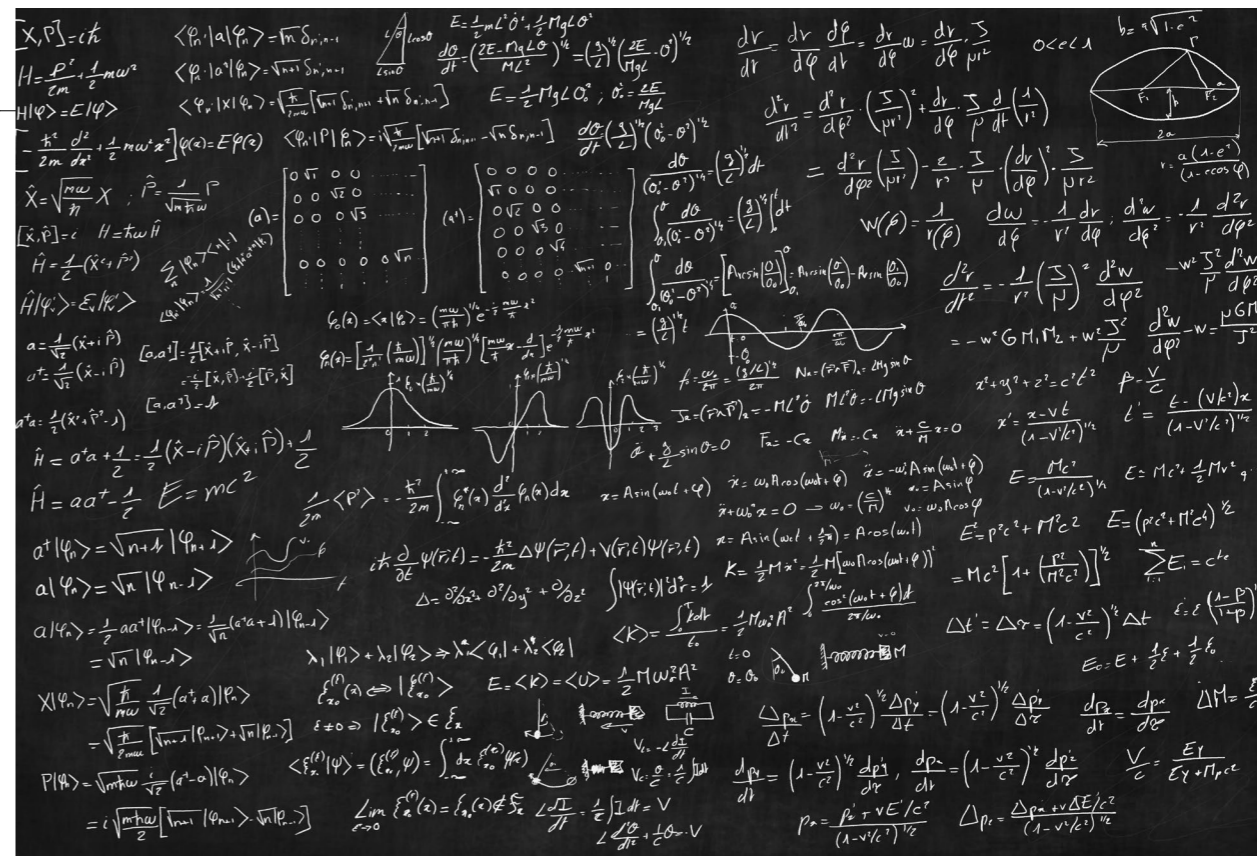
Ono has been focused on another Millennium Problem: the Riemann hypothesis, which involves prime numbers and their distribution. In 2019 he and his colleagues published a paper in the *Proceedings of the National Academy of Sciences USA* that reexamined an old,

formerly abandoned approach for working toward a solution. In an accompanying commentary, Enrico Bombieri, a mathematician at the Institute for Advanced Study in Princeton, N.J., and a 1974 winner of mathematics' highest honor, the Fields Medal, described the research as a “major breakthrough.” Yet Ono says it would be unfounded to describe his work as “anything that suggests that we're about to prove the Riemann hypothesis.” Others have also chipped away at this problem over the years. For instance, mathematician “Terry Tao wrote a nice paper a couple years ago on [mathematician Charles] Newman's

program for the Riemann hypothesis,” Ono says.

PROGRESS ON WHAT WON'T WORK

The fact that just one of the listed problems has been solved is not surprising to the experts—the puzzles are, after all, long-standing and staggeringly difficult. “The number of problems that have been solved is one more than I would expect” to see by now, says Manjul Bhargava, a mathematician at Princeton University and a 2014 Fields medalist. Bhargava himself has reported multiple recent results connected to the Birch and Swinnerton-Dyer



conjecture, including one in which he says he and his colleagues “prove that more than 66 percent of elliptic curves satisfy the Birch and Swinnerton-Dyer conjecture.”

None of the problems will be easy to solve, but some may prove especially intractable. The P versus NP problem appears so difficult to solve that Scott Aaronson, a theoretical computer scientist at the University of Texas at Austin, calls it “a marker of our ignorance.” This problem concerns the issue of whether questions that are easy to verify (a class of queries called NP) also have solutions that are easy to find (a class called P).^{*} Aaronson has written extensively about the P versus NP problem. In a paper published in 2009 he and Avi Wigderson, a mathematician and computer scientist at the Institute for Advanced Study and one of the winners of the 2021 Abel Prize, showed a new barrier to proving that the P class is not the same as the NP class. The barrier that Aaronson and Wigderson found is the third one discovered so far.

“There’s a lot of progress on showing what approaches will not work,” says Virginia Vassilevska

Williams, a theoretical computer scientist and mathematician at the Massachusetts Institute of Technology. “Proving that P [is] not equal to NP would be an important stepping-stone toward showing that cryptography is well founded,” she adds. “Right now cryptography is based on unproved assumptions,” one of which is the idea that P is not equal to NP. “In order to show that you cannot break the cryptographic protocols that people need in modern computers,” including ones that keep our financial and other online personal information secure, “you need to at least prove that P is not equal to NP,” Vassilevska Williams notes. “When people have tried to pin me down to a number,” Aaronson says, “I’ll give a 97 percent or 98 percent chance that P is not equal to NP.”

CLIMBING MOUNT EVEREST

Searching for solutions to the prize problems is similar to trying to climb Mount Everest for the first time, Ono says. “There are various steps along the way that represent progress,” he adds. “The real question is: Can you make it to base camp? And if you can, you still know you’re very far.”

For problems such as the Birch

and Swinnerton-Dyer conjecture and the Riemann hypothesis, Ono says, “surely we’re at Nepal”—one of the countries of departure for climbing the mountain—“but have we made it to base camp?” Mathematicians might still need additional “gear” to trek to the peak. “We’re now trying to figure out what the mathematical analogues are for the high-tech tools, the bottles of oxygen, that will be required to help us get to the top,” Ono says. Who knows how many obstacles could be sitting between current research and possible solutions to these problems? “Maybe there are 20. Maybe we’re closer than we think,” Ono says.

Despite the difficulty of the problems, mathematicians are optimistic about the long term. “I hope very much that while I’m president of the Clay institute, one of them will be solved,” says Bridson, who notes that CMI is in the process of strategizing about how to best continue raising awareness about the problems. “But one has to accept that they’re profoundly difficult problems that may continue to shape mathematics for the rest of my life without being solved.”

—Rachel Crowell

Mysterious Fast Radio Bursts Come in Two Distinct Flavors

A trove of new detections suggests that the bursts could be the result of at least two separate astrophysical phenomena

A radio telescope in Canada has detected 535 fast radio bursts, quadrupling the known tally of these brief, highly energetic phenomena in one go. The long-awaited results show that these enigmatic events come in two distinct types—most bursts are one-off events, with a minority repeating periodically and lasting at least 10 times longer on average.

The findings strongly suggest that fast radio bursts could be the result of at least two distinct astrophysical phenomena. “I think this really just nails it that there is a difference,” says study co-author Kiyoshi Masui, an astrophysicist at the Massachusetts Institute of Technology.

The overnight jump in the available data has put the radio astrono-

The CHIME radio telescope has detected 535 fast radio bursts in its first year of operation



my community into a tizzy. “I woke up this morning, and all my Slack channels were full of people talking about the papers,” says Laura Spitler, an astrophysicist at the Max Planck Institute for Radio Astronomy in Bonn, Germany, who co-discovered the first repeating burst in 2016 using the now collapsed Arecibo telescope in Puerto Rico.

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) collected the events in its first year of operation, between 2018 and 2019. The team announced its results during a virtual meeting of the American Astronomical Society on June 9 and posted four preprints on the online repository arXiv.

REPEATERS AND ONE-OFFS

Located near Penticton in British Columbia, CHIME is a telescope with no moving parts. It comprises four half-pipe antennas, each 100 meters long. At any given time, it observes one narrow strip of the sky above it. But as Earth rotates, the telescope scans the sky, and digital processing chips collect its signals to form an image.

CHIME was initially conceived to map the distribution of matter in the

universe, but a complex kit of extra electronics was added in its design so that it could pick up fast radio bursts as well. Spitler recalls that many workers in the field had been skeptical about the telescope’s potential for detecting the bursts, but the latest announcement has vindicated it. “They’re actually meeting their prediction,” Spitler says. “It’s extremely impressive.”

Although the jury is still out on what causes fast radio bursts, the CHIME results seem to cement the idea that there are at least two distinct types. Sixty-one of the 535 detected were “repeaters”—they came from 18 sources that have been seen emitting bursts multiple times. The two groups

of bursts differ in duration, with one-off events being much shorter. Repeaters also emit on a much narrower band of radio frequencies than do one-off bursts.

“It’s by far the most compelling evidence that there are two populations,” Spitler says.

Until now, the evidence for this was not strong: some astronomers argued that nonrepeating bursts could just have been repeaters that had not been observed for long enough to see them burst again. “It doesn’t mean the phenomenon is wildly different, but it could be,” Masui adds.

Fast radio bursts tend to be detected over one second or more. But this duration is misleadingly long:

as signals travel across millions of light-years of space, intergalactic matter tends to smear radio waves across the spectrum, a phenomenon known as dispersion. As a result, lower-frequency waves can arrive at Earth with a delay of several seconds compared with higher-frequency ones. Researchers have calculated that, at the source, the emission of a radio burst typically lasts only milliseconds. During that time, the source of a burst can emit 500 million times more energy than the sun over a comparable amount of time.

The extent of this dispersion of wavelengths provides a rough indication of how far the waves had to travel. So far all bursts have been

shown to originate in other galaxies, except for one event that occurred in the Milky Way.

The CHIME team reported that the bursts' sources seemed to be evenly spread across the sky. Only a handful could be traced to any particular galaxy.

ORIGIN THEORIES

In recent years researchers have monitored some the regions of the sky that produced bursts in the past and in some cases have seen them reoccur with regular periodicity. The “repeater” discovered by Spitler and her collaborators in 2016, for example, has cycles of activity lasting a day or so—emitting several bursts per hour—and repeating every 160 days.

This regular repetition offers some clues to what might be causing the bursts. One possible explanation, Spitler says, is that repeaters could occur when a highly magnetized neutron star circles around an ordinary star in an elongated orbit. As the neutron star periodically gets closer to its companion, bursts could result from its magnetic field scattering the highly energetic stellar wind.

Nonrepeaters, on the other hand, could be the result of cataclysmic

events, such as the collisions of neutron stars or magnetic storms in young neutron stars called magnetars. The Milky Way event was linked to a known magnetar. But the magnetar theory has been cast into doubt by the finding, reported in June, of a burst from a “globular cluster” in the galaxy M81. Globular clusters are dense collections of very old stars and are considered unlikely to host magnetars.

The first discovery of a fast radio burst in 2007 came as a shock to researchers, and for many years only a few were known, Masui recalls. Theorists came up with a plethora of possible explanations, and the running joke was that the theories outnumbered the actual events. Now CHIME has reversed that trend, he says: “I don’t think theorists will catch up with us.” And this first catalog of bursts is only the beginning: since those results were collected, the team has continued to detect many more fast radio bursts and will publish them for years to come.

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—Davide Castelvecchi

See the Highest-Resolution Atomic Image Ever Captured

Scientists achieved a record level of visual detail with an imaging technique that could help develop future electronics and better batteries

Behold the highest-resolution image of atoms ever seen. Cornell University researchers captured a sample from a crystal in three dimensions and magnified it 100 million times, doubling the resolution that earned the same scientists a Guinness World Record in 2018. Their work could help develop materials for designing more powerful and efficient phones, computers and other electronics, as well as longer-lasting batteries.

The researchers obtained the image using a technique called electron ptychography. It involves shooting a beam of electrons, about a billion of them per second, at a target material. The beam moves infinitesimally as the electrons are fired, so they hit the sample from slightly different angles each time—sometimes they pass through cleanly, and

other times they hit atoms and bounce around inside the sample on their way out.

Cornell physicist David Muller, whose team conducted the recent study, likens the technique to playing dodgeball against opponents who are standing in the dark. The dodgeballs are electrons, and the targets are individual atoms. Although Muller cannot see the targets, he can see where the “dodgeballs” end up, thanks to advanced detectors. Based on the speckle pattern generated by billions of electrons, machine-learning algorithms can calculate where the atoms were in the sample and what their shapes might be.

Previously, electron ptychography had only been used to image extremely flat samples: those merely one to a few atoms thick. The new study, published in *Science*, now allows it to capture multiple layers tens to hundreds of atoms thick. That makes the technique much more relevant to materials scientists, who typically study the properties of samples with a thickness of about 30 to 50 nanometers. (That range is smaller than the length your fingernails grow in a minute but many times thicker than what electron

ptychography could image in the past.) “They can actually look at stacks of atoms now, so it’s amazing,” says Andrew Maiden, an engineer at the University of Sheffield in England, who helped to develop ptychography but was not involved with the new study. “The resolution is just staggering.”

This marks an important advancement in the world of electron microscopy. Invented in the early 1930s, standard electron microscopes made it possible to see objects such as polioviruses, which are smaller than the wavelengths of visible light. But electron microscopes had a limit: increasing their resolution required raising the energy of the electron beam—and eventually the necessary energy would become so great that it would damage the sample. One way to avoid this problem was ptychography, which researchers developed in theory in the 1960s. But because of limitations in detectors and computational power, as well as the complex math required, it was decades before the technique was put into practice. Early versions only worked with visible light and x-rays, not the electron beams required to image

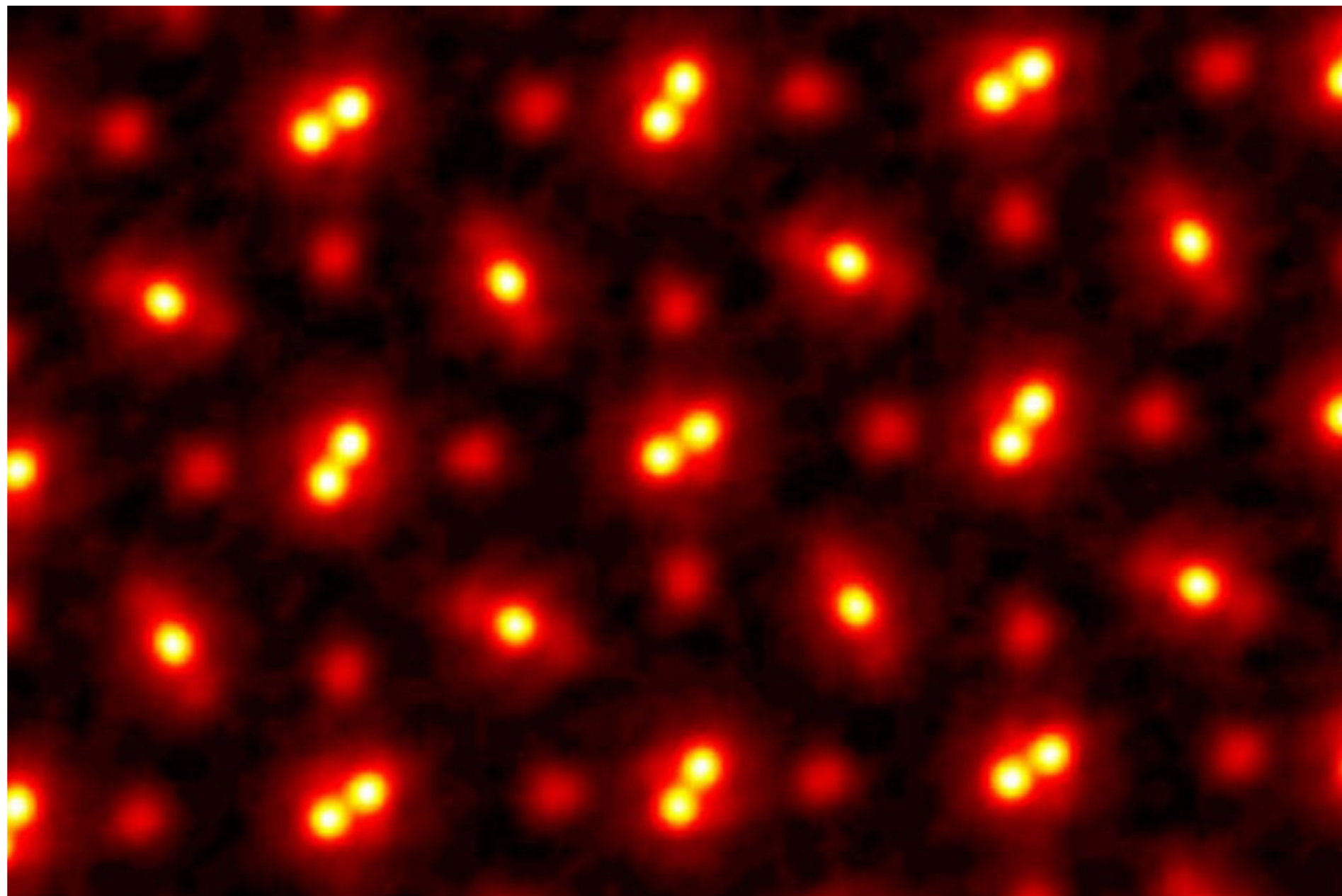


Image shows an electron ptychographic reconstruction of a praseodymium orthoscamdate (PrScO3) crystal, zoomed in 100 million times.

atomic-size objects. Meanwhile scientists kept finding ways to improve electron microscopes, which worked so well that electron

ptychography could not keep up. “You had to be a true believer in ptychography to be paying attention to it,” Muller says.

It was only in the past several years that Muller and his team developed a detector good enough for electron ptychography to work experimentally.

By 2018 they had figured out how to reconstruct two-dimensional samples with the technique, producing “the highest-resolution image by any method in the world,” Muller says—which won that Guinness World Record. The researchers did so with a lower-energy wavelength than other methods, allowing them to better preserve their samples.

Thicker samples, however, presented multiple challenges. Instead of bouncing just once before detection, an electron wave ricochets around atoms in a three-dimensional sample. “You know where it ended up, but you don’t know what path it took in the material,” Muller says. This pinballing is called the “multiple scattering problem,” and he and his team spent the past several years trying to solve it. With enough overlapping speckle patterns and computing power, they found they could work backward to determine which layout of atoms produced a given pattern. The researchers did so by fine-tuning a model until the speckle pattern it generated matched the experimentally produced one.

Solving the multiple scattering problem is a major advancement, Muller says. Referring to the resolu-

tion his team’s technique can capture for samples 300 atoms thick or smaller, he contends that “we can do better than anyone else, and we can do better than anyone else by factors of two to four.”

Such high-resolution imaging techniques are essential for developing the next generation of electronic devices. For example, researchers are looking to move beyond silicon-based computer chips in search of more efficient semiconductors. To make this happen, engineers need to know what they are working with at an atomic level—which means taking advantage of technologies such as electron ptychography. “We have these tools sitting there, waiting to help us optimize what will become the next generation of devices,” says J. Murray Gibson, dean of the Florida A&M University–Florida State University College of Engineering, who was not involved in the new study. “Without these tools, we couldn’t do it.”

Batteries are a particularly promising area for applying imaging techniques such as electron ptychography, says Roger Falcone, a physicist at the University of Califor-

nia, Berkeley, who was also not involved with the research. “How do we make the structure of batteries,” he asks, “such that they can store a lot of energy and yet still be safe?” This is an essential question, especially for the transition from fossil fuels to renewable energies, including wind and solar. “Imaging technologies are very important to improving batteries because we can look at the chemical reactions in detail,” Falcone says.

But there is still a long way to go. For electron ptychography to lead to a new breakthrough for your cell phone or laptop, it must do more than take a picture—it has to be capable of precisely locating an individual atom in a material. Although the researchers demonstrated how the

“To the extent that you invent a new tool like a high-resolution microscope, my sense is that you tend to be surprised [by] what problem it’s applied to solve. People will look at things that we can’t even imagine now—and solve a problem that we’re not even sure we have yet.”

—Roger Falcone

technique could do so theoretically, they have not yet performed an experimental demonstration. “With any new technique, it takes a bit of time for your fellow researchers to try this out and see if it bears out into real, practical uses,” says Leslie Thompson, former manager of materials analysis and characterization at IBM Research–Almaden, who was not part of the study.

“To the extent that you invent a new tool like a high-resolution microscope, my sense is that you tend to be surprised [by] what problem it’s applied to solve,” Falcone adds. “People will look at things that we can’t even imagine now—and solve a problem that we’re not even sure we have yet.”

—Anna Blaustein

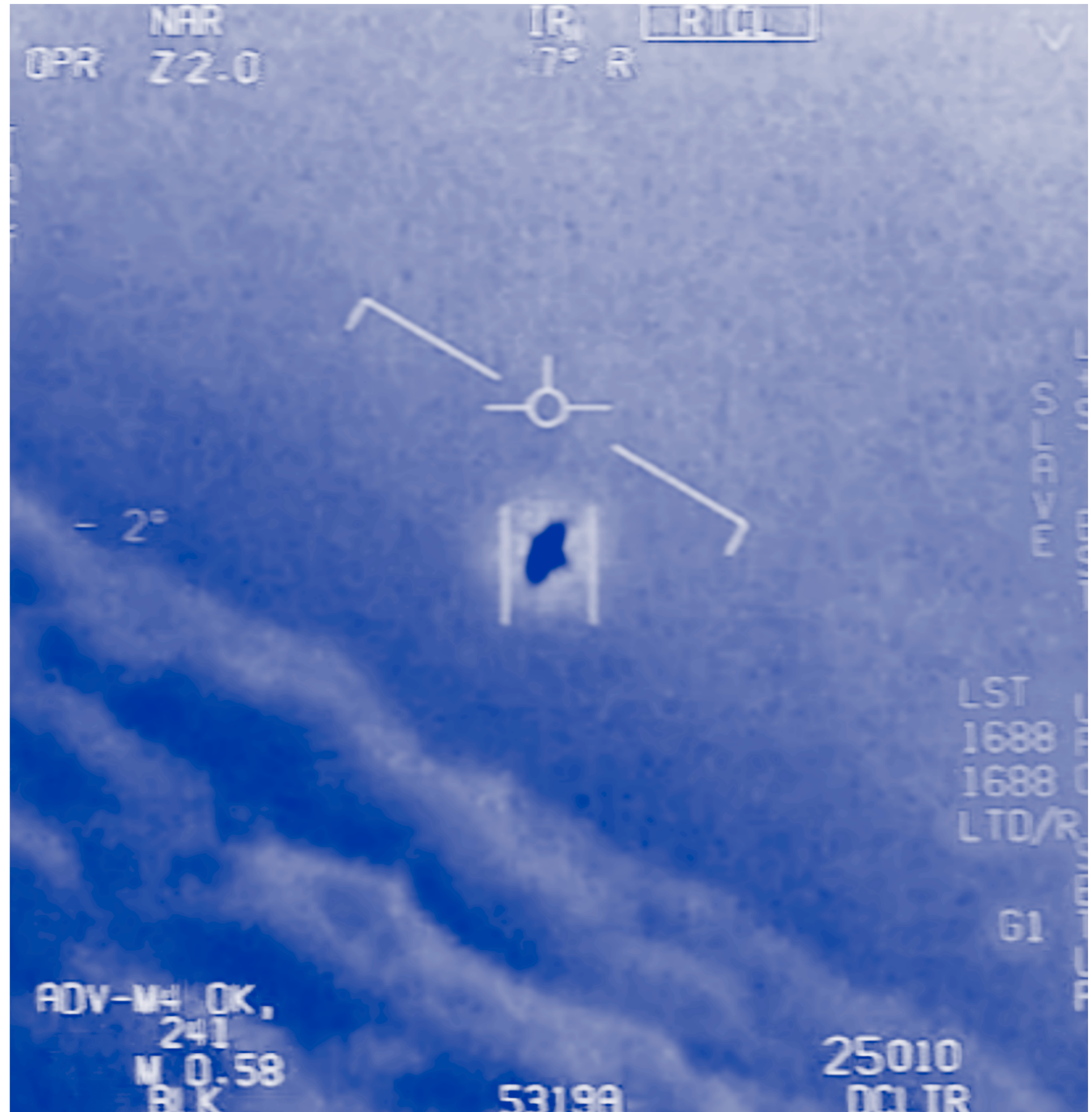
Experts Weigh in on Pentagon UFO Report

The vast majority of examined incidents were not caused by U.S. advanced technology programs, the report concludes.

So what's going on?

By Leonard David

Still from a video released by the U.S. Department of Defense showing an encounter between a navy F/A-18 Super Hornet and an unknown object.



Leonard David is author of *Moon Rush: The New Space Race* (National Geographic, 2019) and *Mars: Our Future on the Red Planet* (National Geographic, 2016). He has been reporting on the space industry for more than five decades.

FOR MORE THAN A DECADE THE U.S. DEPARTMENT OF DEFENSE HAS BEEN QUIETLY cataloging and investigating scores of bizarre encounters—most from the U.S. Navy—of ships and fighter jets tangling with, or being tailgated by, unidentified flying objects (UFOs). Beginning in 2017, videos and eyewitness accounts of these weird sightings found their way into public view, ultimately spurring Congress to demand that the Pentagon produce a report summarizing all that the U.S. government knows about so-called unidentified aerial phenomena, or UAP (an alternative term with considerably less stigma than the much maligned “UFOs”).

Produced under the auspices of a Pentagon group called the UAP Task Force, an unclassified version of the report was released in late June. On establishing the task force, the DOD released an accompanying statement explaining the justifications for its existence: “The safety of our personnel and the security of our operations are of paramount concern. The Department of Defense and the military departments take any incursions by unauthorized aircraft into our training ranges or designated airspace very seriously and examine each report. This includes examinations of incursions that are initially reported as UAP when the observer cannot immediately identify what he or she is observing.”

ASSESSING THE “ALIEN” HYPOTHESIS

Meanwhile all this strangeness has garnered considerable media attention, from front-page stories in the *New York Times* to 13,000-word articles in the *New Yorker*, as well as prominent coverage on *60 Minutes* and other

prime-time television programs. Through it all, a sizable contingent of true believers have steadily proclaimed, “We told you so,” insistent in their conviction that, whether called UFOs or UAP, the entities seemingly slipping through our skies are actually alien spacecraft—and have been visiting Earth for a very long time.

Those deeply entrenched public beliefs, paired with the apparent reinvigoration of investigative interest in these incidents at the highest levels of government, can lead to dazzling speculations. Might we be on the verge of a formal disclosure—backed by irrefutable evidence—that humankind is not alone and is indeed being monitored by extraterrestrial civilizations? Or could it be that UAP are entirely homegrown products of revolutionary and clandestine technological advances, whether by other countries now challenging American airspace or by the U.S. itself as part of some supersecret domestic program meant to detect flaws in the nation’s defenses? The mind boggles.

The *New York Times* provided a cursory preview of its contents in an article on June 3. Citing anonymous senior officials familiar with the report’s contents, the story said that the assessment has come up short of explaining what UAP are and that it provides no evidence to link them with any putative alien visitation—despite reviewing more than 120 incidents from the past 20 years. The report’s firmest conclusion, it seems, is that the vast majority of UAP happenings and their surprising maneuvers are not caused by any U.S. advanced technology programs.

Last, according to the *New York Times* article, the final report includes a “classified annex” of information deemed unsuitable for public release—leaving more than enough room for die-hard UFO advocates to remain convinced that the U.S. government is hiding the truth.

NO “BIG REVEAL”

Andrew Fraknoi, an astronomer at the Fromm Institute for Lifelong Learning at the University of San Francisco, echoes the widely held sentiment among scientists that, for decades, the media has lavished too much attention on sensational claims that vague lights in the sky are actually extraterrestrial spacecraft. “Recently there has been a flurry of misleading publicity about UFOs [based on military reports]. A sober examination of these claims reveals that there is a lot less to them than first meets the eye,” Fraknoi says. Given sufficient evidence (which, arguably, many of the recent reports fail to provide), UFO sightings can essentially always be tied to terrestrial or celestial phenomena, such as lights from human-made

vehicles and reentering space junk, he adds.

There is not going to be any “big reveal,” says Robert Sheaffer, a leading skeptical investigator of UFOs. “There are no aliens here on Earth, and so the government cannot ‘disclose’ what it does not have. Some people think that the government knows more about UFOs, or UAP, than the public, but it’s clear that they know less on the subject than our best civilian UFO investigators, not more.”

The DOD employs some very competent photographic analysts and other technical experts, “none of whom obviously were consulted in this comedy of errors,” Sheaffer says. “The Pentagon has already suffered enough embarrassment from the [apparent] incompetence of its UAP Task Force.” He says it is time to rein in such “rampant foolishness” and ensure that proper experts will shape the task force’s conclusions rather than “clueless, self-important people who don’t even recognize out-of-focus images when they see them.”

REAL ISSUES

Skeptical science writer Mick West has taken on the chore of analyzing the spate of UAP videos released by the U.S. military, steadfastly investigating how some of the incidents could merely be mirages from flaws in newly deployed radar systems, as well as various sorts of well-understood visual artifacts regularly seen in cameras. Despite his work to debunk the recent claims, West maintains that reports of mysterious aircraft stalking military assets should be taken quite seriously.

“First, there’s a set of very real issues that could be grouped together as ‘UAPs’ or ‘UFOs,’” West says. “Any time something unidentified shows up in restricted airspace, then that’s a real problem that needs solving.” There have been many reports of drones above or near restricted areas, he notes. “We know that drones have been used for terrorist attacks, and drones will very much be a significant factor in future conflicts,” West says. “So we need to

figure out how to identify and mitigate such things.”

Another real issue is that pilots sometimes see things that they cannot readily identify, West says, and they may misidentify such objects. Regardless of what such pilots actually observe, this is a problem. “If something there is hard to identify—like a novel drone—then we need to figure out how to identify it,” he says. “If the pilots are making mistakes, then we need to figure out why.”

THE “DISCLOSURE” FEEDBACK LOOP

“The advocates of alien disclosure are encroaching on these real issues of UAPs,” West says. These believers take mundane videos of incidents that are simply unidentified, he says, then reframe them as evidence of extraordinary technology—which, of course, is intended to mean “aliens,” even if enthusiasts for that hypothesis will not explicitly say so. This cultivates credulous media attention, which in turn creates a feedback loop of public interest, more media and then pressure on politicians to “do something.”

“All the while, the military makes no comments, because that’s their modus operandi. Military things are assumed classified by default, and there is nothing compelling them to clear things up,” West says. In the end,

**“There are no aliens here on Earth,
and so the government cannot ‘disclose’ what it
does not have. Some people think that the government knows
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—Robert Sheaffer

he hopes that the report represents the views of serious people finally stepping in to clear up what is—and is not—going on.

“I expect much discussion and information about the real issues of unidentified flying objects. But I do not anticipate it will have much that will please the UFO enthusiasts,” West says.

WAIT AND SEE

One person who is taking a “wait and see” attitude about the report is Ravi Kumar Kopparapu, a research scientist in planetary studies at NASA’s Goddard Space Flight Center. The history of scientific studies of UAP in the U.S. is not limited to the recently released video snippets, which is a good reminder to avoid painting the whole phenomenon with one broad brush, he says. Additionally, this is not a U.S.-specific issue, nor is it limited to observations by U.S. armed forces.

“There may not be a single explanation to all such observations. What I would suggest is that we not leap to any conclusions when the findings of the report are made public,” Kopparapu says. “The report would be immensely helpful if the data that informed it are made publicly

available so that more experts and scientists can look at it and hopefully reach a scientific consensus on the nature of some of the unexplained events. Otherwise, there will always be conspiracy theories shrouding, and inhibiting, a proper scientific investigation of UAPs.”

A similar view is held by Mark Rodeghier, scientific director of the Center for UFO Studies, who says openness should be prioritized as much as possible in future investigations. “We don’t know whether the UFO problem is an intelligence one, due to foreign adversaries, but we do know, from its long history, that it is absolutely a scientific problem that deserves serious attention,” he says. “In a subject that has been too long ignored, downplayed and ridiculed, the government and scientific community should study UFOs openly and, importantly, with an open mind.”

WANTED: SCIENTIFIC INQUIRY

Harvard University astrophysicist Avi Loeb says the significance of the UAP Task Force report will depend on the evidence it discloses, which has remained mostly unknown. “But this focus on past reports is misguided,” he says. “It would be prudent to progress forward with our finest instruments rather than examine past reports. Instead of focusing on documents that reflect decades-old technologies used by witnesses with no scientific expertise, it would be far better to deploy state-of-the-art recording devices, such as cameras or audio sensors, at the sites where the reports came from and search for unusual signals.”

Loeb goes a step further, saying he is willing to sign up to help unravel the UAP/UFO saga. “Personally, I will be glad to lead scientific inquiry into the nature of these reports and advise Congress accordingly,” he says. “This could take the form of a federally designated committee or a privately funded expedition. Its most important purpose would be to inject scientific rigor and credibility into the discussion.”

HISTORY REPEATS ITSELF

For some seasoned investigators, such as William Hartmann, a senior scientist emeritus at the Planetary Science Institute, headquartered in Tucson, Ariz., the current dustup over an influential government report on UFOs is a reminder that, eventually, everything old becomes new again.

Hartmann was a photography consultant and a co-author of the University of Colorado UFO Project’s report *Scientific Study of Unidentified Flying Objects*. Funded by the U.S. Air Force from 1966 to 1968, that investigative effort was led by physicist Edward Condon, and it had dismal effects on subsequent scientific investigations. The extensive study of UFOs, Condon and his co-authors concluded, is simply not a fruitful field in which to seek major discoveries and “probably cannot be justified in the expectation that science will be advanced thereby.”

Reflecting on his work for the project, also called the Condon committee, Hartmann says that none of the photographic evidence he examined could establish anything extraordinary about the observed phenomena. “We proved that some of [the cases], including classic photos still being trotted out, were fake,” he says. “That fact alone makes it extremely difficult to apply straight scientific techniques because we know some, not necessarily all, of the data we were given were carefully prepared to delude us. [That is] not quite like astronomy, where we can assume that the photons coming through our telescope atop Mauna Kea in Hawaii are not put in there by a hoaxer.”

“To put it another way, if you think there could be a real alien spaceship among a pile of photos you are given, but you know that some of the photos are fakes, then it is very hard to prove that any single one of them is proof of an alien visitation,” Hartmann says. “I’d want to see multiple, clear photos or detections by witnesses who don’t know each other, from multiple cities, viewing from multiple directions, before getting very excited.”

Still, he adds that ever since his experience working on the Condon committee, he cannot escape “the feeling that there may be electromagnetic phenomena in the atmosphere that we still don’t understand.”

THE TRUTH IS OUT THERE

Sarah Scoles is author of the 2020 book *They Are Already Here: UFO Culture and Why We See Saucers*. She senses that the report’s full details will not be as revelatory as some hope.

“At various times during the 20th century, the military has undertaken studies of UFOs to determine, largely, whether what people are seeing represents a national security threat,” Scoles says. “This report doesn’t, then, seem seminal, because it’s doing a 21st-century version of that same thing.”

That said, Scoles feels an unbiased analysis of available data could shed light on the true frequency of UAP observations—and perhaps on the characteristics and possibly identities of these sightings. “One problem with UFO/UAP research is that it often doesn’t resemble traditional scientific research in terms of rigor,” she says.

The task force report could quantify and analyze a wide swath of data, Scoles hopes, with the requisite background knowledge of sensor capabilities, current domestic and foreign military capabilities, and so on. If so, that would be a welcome change from previous high-profile studies, she concludes.

Where does this leave us? The truth, of course, is somewhere out there, whether or not it appears in the pages of the UAP Task Force report. But for now, the odds seem to be against the U.S. government knowing what it is, let alone revealing it anytime soon. **SA**



A Modest Proposal: Let's Change Earth's Orbit

What's the worst that could happen?

By Maddie Bender



During a congressional hearing recently, Representative Louie Gohmert of Texas asked a U.S. Forest Service official if her organization or the Bureau of Land Management could change the orbit of the moon or Earth to reverse the effects of human-caused climate change. That seems like a perfectly reasonable idea, doesn't it? Let's do it.

First, we must take stock of what we have—the givens in what will be our equation for moving Earth. Our planet orbits the sun at an average distance of 149.6 million kilometers, and it soaks up enough sunlight to have an average temperature of about 15 degrees Celsius. The latter figure is, however, an increase of slightly more than one degree C from Earth's typical temperature across the past century. In short, this world is running a low-grade fever. According to current consensus estimates, that fever is likely to get much worse if left unchecked, raising Earth's average temperature by another one degree C by the 2060s. Such an increase would render some currently people-packed parts of the planet effectively uninhabitable and threaten the sustainability of global civilization as we know it.

Radiative equilibrium, the balance between incoming energy from the sun's rays and energy emitted from Earth, is key to our understanding of our planet's changing temperature, says Britt Scharringhausen, a planetary astronomer at Beloit College. It is described in the equation shown on page 23, as scribbled out by Scharringhausen.

The page from her lab notebook shows an equation for determining a planet's radiative equilibrium, which sets its effective temperature.

Here T_e is Earth's temperature, T_\odot is the sun's temperature, R_\odot is the sun's radius, X is the distance to the sun, and A is Earth's albedo, or reflectivity. Albedo measures how well our planet reflects solar energy, where 0 would be perfect absorption and 1 would be perfect reflection. There is a connection between climate change and albedo: snow and ice, for instance, have a high albedo, reflecting up to 90 percent of the sunlight that hits them back to outer space. Anthropogenic warming causes snow and ice caps to melt, which can make Earth's albedo decrease. That, in turn, eventually leads to a higher average planetary temperature.

Some variables in this equation are changing naturally. Our star is very slowly swelling and brightening, becoming slightly larger and more luminous as it ages. Ethan Siegel, a theoretical astrophysicist and science writer, says that while it will take the sun on the order of 100 million years to increase in luminosity by 1 percent, our greenhouse-gas-emitting global civilization is projected to increase the solar energy retained by Earth by 1 percent over the next few hundred to 1,000 years.

To make Earth cooler, we need to decrease a variable on the right side of the equation: We can't easily lower the sun's temperature or radius—and clearly meaningful reductions to our heat-trapping, albedo-shifting greenhouse gas emissions are out of the question. So let's take Representative Gohmert's advice and simply increase X ,

the distance to the sun. All we have to do is find a way to move all 5.972 septillion kilograms of Earth's mass farther away from our star. Easy, right?

By Scharringhausen's calculations, a three-degree-C decrease in temperature to counteract current and near-future anthropogenic warming would require us to move our planet an additional three million kilometers from the sun. Using another back-of-the-envelope calculation, Scharringhausen finds that 5×10^{31} joules could push all 5,972,000,000,000,000,000,000,000 kilograms of Earth's mass three million kilometers out from its present orbit. These numbers present challenges for Representative Gohmert's plan because annual global electricity production is around 10^{19} joules, or 0.0000000000002 percent of what we'd need to move the globe. That's also assuming we can apply all that energy to Earth at 100 percent efficiency, which, thanks to the laws of thermodynamics, is physically impossible.

Setting aside such particulars, we haven't addressed what form this applied energy would take. There is the literal nuclear option: one method that scientists have proposed to move an asteroid is to detonate a nuclear bomb near it, Scharringhausen says. "It will basically vaporize part of the asteroid, and that escaping rock vapor acts like rocket exhaust and will push the asteroid along," she explains.

Scaled up, such a mechanism could, in principle, provide enough oomph to shift a planet's orbit. Still, it would take a billion times more nuclear explosions than we have ever set off to move Earth the required distance,

Maddie Bender is a 2021 AAAS Mass Media Fellow at *Scientific American*. She recently received an MPH in microbial disease epidemiology from the Yale School of Public Health.

or the equivalent of dropping an atomic bomb every second for 500 years, according to Geza Gyuk, director of astronomy at the Adler Planetarium in Chicago. The strategy of constantly detonating nuclear bombs near Earth's surface with the goal of vaporizing parts of it to act as rocket exhaust also has several drawbacks. For our purposes, the most notable deleterious effect is that the blasts themselves would heat up the planet, counteracting the stated goal of reversing global warming.

A gentler option would be to siphon off the energy of other celestial objects, such as passing asteroids or comets, by engineering close planetary flybys. This technique is regularly used in reverse, with great success, by spacecraft that boost their speed by passing close to a planet to steal a portion of its orbital energy. For moving our planet, the issue with the method is scale, Siegel says: the total mass of the asteroid belt is only 4 to 5 percent of that of the moon, or 0.05 to 0.06 percent of that of Earth. Using the mass of the entire asteroid belt in flybys would migrate Earth away from the sun by less than 748,000 kilometers, or a quarter of the distance we would need, he says. And a single off-course collision with our planet would spark destruction approaching that caused by the asteroid impact that eradicated the dinosaurs in a global mass extinction.

Fortunately, we have a much more massive space rock sitting in our backyard: the

moon itself. Could we "cut" the gravitational string connecting the moon to the Earth, thereby slingshotting our planet into a wider orbit? Not in any way that we're capable of doing today, Siegel says, and the consequences would be disastrous. Besides having greatly reduced tides, a moonless Earth would have much darker nights, shorter days and extreme, unpredictable seasons because of a destabilized axis of rotation.

What if instead of getting rid of our natural satellite altogether, we only change its orbit around Earth? Increasing the radius of the moon's orbit by 10 percent would affect Earth's own trajectory around the sun in the long term, says Matteo Ceriotti, a rocket scientist at the University of Glasgow's James Watt School of Engineering.

We could extract and accelerate material off the moon, Ceriotti says. Using a 100-gigawatt laser or one with about the power capacity of every single wind turbine in the U.S., it would take 300 trillion years to lift sufficient amounts of material from the lunar surface. There is always the aforementioned nuclear option, too, which could be used to move the moon rather than Earth. Another, less messy choice would be to manually extract lunar material with conventional rockets.

Page from planetary astronomer Britt Scharringhausen's lab notebook shows a handwritten equation for determining a planet's radiative equilibrium (*highlighted in green*), which sets its effective temperature.

Radiative Equilibrium:

Balancing sunlight absorbed with light re-emitted by Earth

$$T_{eq} = T_{\odot} \sqrt[4]{1-A} \sqrt{\frac{R_{\odot}}{2x}} \quad \odot = \text{Sun} \quad \oplus = \text{Earth}$$

Where T_{\odot} = Sun's temperature, 5600K
 A = albedo of earth, x = Earth-Sun distance.

For Earth at current location

$$T_{eq} = 255K$$

For small changes in distance from the Sun, x , sorry, calculus!

$$\Delta T = \frac{dT}{dx} \Delta x$$

$$\Delta T = T_{\odot} \sqrt[4]{1-A} \sqrt{\frac{R_{\odot}}{2}} \left(-\frac{1}{2} x^{-3/2}\right) \Delta x$$

$$= -\frac{1}{2} \underbrace{T_{\odot} \sqrt[4]{1-A} \sqrt{\frac{R_{\odot}}{2x}}}_{\text{The original } T_{eq}!} \frac{1}{x} \Delta x$$

$$\text{So } \Delta T = -\frac{1}{2} (255K) \frac{\Delta x}{x}$$

$$\text{or } \Delta x = -2 \frac{\Delta T}{255K} x$$

So for 3K of cooling

$$\Delta x = \frac{-2 (-3K)}{255K} \cdot 1 \text{ AU}$$

$$= 0.02 \text{ AU} \times \frac{1.496 \times 10^8 \text{ km}}{1 \text{ AU}}$$


$$= 3 \times 10^6 \text{ km}$$

“If we were able to build a spaceport on the moon and build a rocket equivalent to SpaceX’s Falcon Heavy to lift off moon material into deep space, we would need 7×10^{16} launches,” Ceriotti says. That’s 70,000 trillion rocket launches. For comparison, during the entirety of the space age, humankind has only managed to achieve 70,780 launches, and more than half of them did not leave Earth’s atmosphere.

Humans could add a twist to the use of asteroids in the flyby idea and instead put them on a collision course with the moon, Gyuk says. We would need kilometer-sized comets to crash into the moon every second for a couple of hundred years to make a substantial difference. Again, though, an off-course projectile could cause a planetary mass extinction event.

Because of the magnitude of the change necessary to increase Earth’s orbit, any intervention would probably need to last for many millions of years at minimum, which raises an unexpected sociological issue, Gyuk says: We don’t have precedent for planning across such vast timescales. And in fact, no civilization in human history has endured more than a mere few thousand years.

Finally, even if humans managed to alter our planet’s orbit using any of these methods, they wouldn’t be able to rest easy, Siegel says. “If we even somehow could make this enormous change in Earth’s orbit,” he says, “it doesn’t absolve us from the responsibility that we’ll keep needing to make this change as long as we keep increasing the greenhouse gas concentration in our atmosphere.”

To my ears, that sounds like a stirring endorsement of our fossil-fuel-addicted status quo! We should immediately prioritize pouring all our energy into changing Earth’s orbit, starting now and lasting forever. Sure, it’s a Sisyphean task in which humanity is Sisyphus and the boulder being eternally pushed uphill is Earth itself. But at least we’d get to keep driving our sweet SUVs! I say we get to work. 

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Avi Loeb is former chair (2011-2020) of the astronomy department at Harvard University, founding director of Harvard's Black Hole Initiative and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. He also chairs the Board on Physics and Astronomy of the National Academies and the advisory board for the Breakthrough Starshot project, and is a member of President's Council of Advisors on Science and Technology. Loeb is the bestselling author of *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth* (Houghton Mifflin Harcourt).

SPACE

A Possible Link between 'Oumuamua and Unidentified Aerial Phenomena

If some UAP turn out to be extraterrestrial technology, they could be dropping sensors for a subsequent craft to tune into. What if 'Oumuamua is such a craft?

A colleague of mine once noted that every morning there is a long line of customers stretching out from a famous Parisian bakery into the street. "I wish someone would wait for my scientific papers with as much anticipation as Parisians eagerly stand by for their baguettes," he said.

There is one exception to this wish, however. It involves fresh scientific evidence that we are not be the only intelligent species in the cosmos.

Recently there have been two sources for such evidence.

First, the interstellar object discovered in 2017,



Artist's impression of the interstellar object 'Oumuamua.

'Oumuamua, was inferred to have a flat shape and seemed to be pushed away from the sun as if it were a lightsail. This "pancake" was tumbling once every eight hours and originated from the rare state of the local standard of rest—which averages over the motions of all the stars in the vicinity of the sun.

Second, the Pentagon delivered a report to Congress stating that some unidentified aerial phenomena (UAP) are real but that their nature is unknown. If UAP originated from China or Russia and were a national security risk, their existence would have never been revealed to the public. Hence, it is reasonable to conclude that the U.S.

government believes that some of these objects are not human in origin. This leaves two possibilities: either UAP are natural terrestrial phenomena, or they are extraterrestrial in origin. Both possibilities imply something new and interesting that we did not know before. The study of UAP should therefore shift from occupying the talking points of national security administrators and politicians to the arena of science where it is studied by scientists rather than government officials.

Many or even most UAP might be natural phenomena. But even if one of them is extraterrestrial, might there be any possible link to 'Oumuamua?

The inferred abundance of 'Oumuamua-like objects is unreasonably large if they're of purely natural origin. With Amaya Moro-Martín and Ed Turner, I wrote [a paper](#) in 2009 calculating the [number of interstellar rocks](#) based on what is known about the solar system and assuming that these rocks were ejected from similar planetary systems orbiting other stars. The population of objects required to explain the discovery of 'Oumuamua [exceeds the expected number](#) of interstellar rocks per unit volume by orders of magnitude. In fact, there should be [a quadrillion](#) 'Oumuamua-like objects within the solar system at any given time, if they are distributed on random trajectories with equal probability of moving in all directions.

But the number is reasonable if 'Oumuamua is an artificial object on a targeted mission toward the sun, aimed to collect data from the habitable

But the number is reasonable if 'Oumuamua was an artificial object on a targeted mission toward the sun, aimed to collect data from the habitable region near Earth. One might even wonder whether 'Oumuamua might have been retrieving data from probes that were already sprinkled on Earth at an earlier time.

region near Earth. One might even wonder whether 'Oumuamua might have been retrieving data from probes that were already sprinkled on Earth at an earlier time. In such a case, 'Oumuamua's thin, flat shape could have been that of a receiver. Hence, 'Oumuamua was pushed by sunlight not for the purpose of propulsion but as a by-product of its thin, flat shape. A similar push by reflection of sunlight without a cometary tail involved the traits of an artificial rocket booster that was identified in 2020 by the same [Pan-STARRS](#) telescope that discovered 'Oumuamua. This artificial object named [2020 SO](#) was not designed to be a [solar sail](#) but had thin walls with a large surface-to-mass ratio for a different purpose.

At this time, the possibility that any UAP are extraterrestrial is highly speculative. But if we entertain this possibility for fun, then the tumbling motion of 'Oumuamua could potentially have been meant to scan signals from all viewing directions. A predecessor to 'Oumuamua could have been a craft that deposited small probes into Earth's atmosphere without being noticed because it visited before Pan-STARRS started its

operations. Along this imaginative line of reasoning, 'Oumuamua could have arranged to appear as coming from the neutral local standard of rest, which serves as the local "galactic parking lot," so that its origin would remain unknown.

But rather than simply wondering about possible scenarios, we should collect better scientific data and clarify the nature of UAP. This can be done by deploying state-of-the-art cameras on wide-field telescopes that monitor the sky. The sky is not classified; only government-owned sensors are. By searching for unusual phenomena in the same geographical locations from where the UAP reports came, scientists could clear up the mystery in a transparent analysis of open data.

As noted in my recent book *Extraterrestrial*, I do not enjoy science-fiction stories, because the story lines often violate the laws of physics. But we should be open-minded to the possibility that science will one day reveal a reality that was previously considered as fiction.

John Horgan directs the Center for Science Writings at the Stevens Institute of Technology. His books include *The End of Science*, *The End of War* and *Mind-Body Problems*, available for free at mindbodyproblems.com. For many years, he wrote the immensely popular blog Cross Check for *Scientific American*.

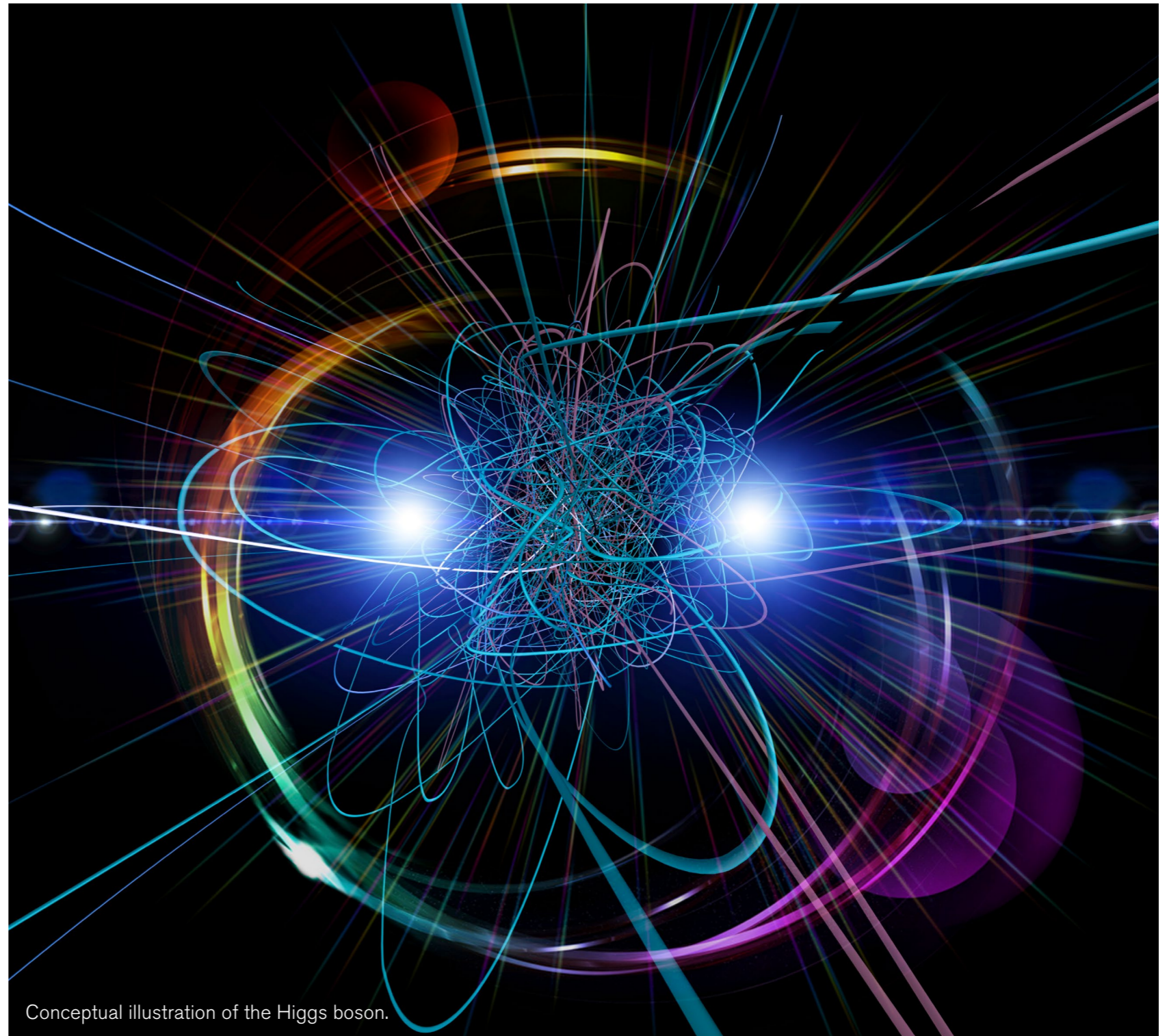
PHYSICS

Can Science Survive the Death of the Universe?

Three physicists envision ways in which the quest for knowledge can last forever

Faith isn't faith if it's based on evidence, so it's wrong to say that I have faith in human progress. Unlike God, progress is objectively real, a demonstrable fact, as much so as evolution. Humanity has gotten wealthier, healthier, freer, more peaceful and smarter. We know more than our ancestors did, and we're learning more all the time. These trends, any reasonable person must acknowledge, constitute progress. The question is: How long can this progress last?

Let me back up a moment. I recently concurred with megapundit Steven Pinker that over the past two centuries we have achieved material, moral and intellectual progress, which should give us hope that we can achieve still more. I expected, and have gotten, pushback. Pessimists argue that our progress will prove to be ephemeral, that we will inevitably succumb to our own nasti-



Conceptual illustration of the Higgs boson.

ness and stupidity and destroy ourselves.

Maybe, maybe not. Just for the sake of argument, let's say that within the next century or two we solve our biggest problems, including tyranny, injustice, poverty, pandemics, climate change and war. Let's say we create a world in which we can do pretty much anything we choose. Many will pursue pleasure, finding ever more exciting ways to enjoy themselves. Others may seek spiritual enlightenment or devote themselves to artistic expression.

No matter what our descendants choose to do, some will surely keep investigating the universe and everything in it, including us. How long can the quest for knowledge continue? Not long, I argued 25 years ago in *The End of Science*, which contends that particle physics, cosmology, neuroscience and other fields are bumping into fundamental limits. I still think I'm right, but I could be wrong. Below I describe the views of three physicists—Freeman Dyson, Roger Penrose and David Deutsch—who hold that knowledge seeking can continue for a long, long time and possibly forever, even in the face of the heat death of the universe.

If you are speculating about our long-term cosmic future, you must confront the second law of thermodynamics, science's most depressing insight into nature. It decrees that closed systems, which don't get infusions of energy from an outside source, tend over time to become more disordered. That's a euphemism for boring. The second law implies that the universe will inevitably lapse into heat death, in which everything, everywhere, is

exactly the same temperature, near absolute zero, and nothing ever happens.

The discovery in the late 1990s that the universe is expanding at an accelerating rate implies that we are approaching heat death, also known as the big chill, at an increasing rate. Not good. As the universe keeps ballooning, stars, including our own sun (after first becoming a red giant and incinerating Earth) and even black holes, will eventually radiate away all their energy, and the universe will go dark, forever. Cosmologists have calculated that we will reach this cosmic dead end—in which time itself ceases, as physics writer George Musser points out—in one googol years. A googol is 10 to the 100th power.

Yeah, that's a long time. (In contrast, the sun is expected to become a red giant and incinerate our planet in a mere five billion years, or five times 10 to the ninth power.) But this dreary prophecy makes all the progress we've achieved seem pathetically insignificant and meaningless, an infinitesimal backward eddy in the universe's tsunamilike slide toward eternal night. All our knowledge seeking will be for naught because everything we have learned will be forgotten as the universe lapses into utter, irreversible mindlessness.

FREEMAN DYSON'S SENTIENT GAS CLOUD

Disturbed by the prospect of cosmic oblivion, scientists have imagined ways in which we can avoid it. A pioneer in such speculation was Freeman Dyson, who died last year at the age of

96. Dyson was provoked into thinking about the long-term fate of the universe in the late 1970s by physicist Steven Weinberg's infamous remark that "the more the universe seems comprehensible, the more it also seems pointless."

In a 1979 paper, "Time without end: Physics and biology in an open universe," Dyson asserts that the universe has a point, a purpose, as long as it harbors intelligence. Eons from now, he conjectures, our descendants may occupy other star systems and galaxies, perhaps after shedding their flesh-and-blood bodies and becoming clouds of sentient gas. Dyson presents mathematical arguments that these beings can, through shrewd conservation of energy, maintain the resources needed to survive, cogitate and communicate in an eternally expanding cosmos.

Our descendants will always have plenty to think about, Dyson insists. He takes heart from Kurt Gödel's 1931 proof that any system of mathematical axioms is "incomplete," posing questions that cannot be answered with those axioms. Gödel's incompleteness theorem implies that both mathematics and physical reality will challenge us with "inexhaustible" problems. Dyson asserts that "no matter how far we go into the future, there will always be new things happening, new information coming in, new worlds to explore, a constantly expanding domain of life, consciousness, and memory."

After I mentioned Dyson's paper in a 2018 column, he e-mailed me to point out that his paper is "obsolete because it assumed a linearly expanding universe, which the cosmologists believed to be

correct in 1979. We now have strong evidence that the universe is accelerating, and this makes a big difference to the future of life and intelligence.” Dyson declined to “speculate further” about our fate in an accelerating cosmos “until the observational evidence becomes clearer.”

ROGER PENROSE’S ETERNAL CYCLIC COSMOS

Roger Penrose, who won a Nobel Prize last year, has carried on Dyson’s project of imagining our cosmic future. In 2005 Penrose was “depressing himself” by “thinking of the wastes of time that stretch ahead of the universe according to the latest cosmological observations, which suggest an ever-accelerating expansion,” according to an article in *Physics World*. Penrose wondered, “Who will be around then to be bored by this apparent overpowering eventual tedium?”

Penrose overcame his funk by inventing a new model of the universe, conformal cyclic cosmology, which he spells out in his 2010 book *Cycles of Time*. The theory holds that our increasingly vacuous cosmos will eventually produce a singularity, a rupture in spacetime similar to the big bang. In this way, an expanding universe can spawn new universes, one after the other, ad infinitum.

Better yet, according to Penrose and a collaborator, each new universe can pass on its accumulated information to the next in the form of the cosmic microwave radiation left over from its big bang. That means the microwave radia-

Dyson asserts that “no matter how far we go into the future, there will always be new things happening, new information coming in, new worlds to explore, a constantly expanding domain of life, consciousness, and memory.”

tion pervading our universe might contain messages from previous universes. In the same way, the knowledge we accumulate may be passed on to inhabitants of future universes. We’re not so insignificant after all!

Early in his career, moreover, Penrose made a mathematical discovery that lends support to Dyson’s claim that the universe will never cease to surprise us. Penrose showed that a class of polygons now called Penrose tiles can combine to form aperiodic patterns, which never repeat themselves. Like the incompleteness theorem of Gödel, and like the Game of Life, a cellular automaton invented by mathematician John Conway, Penrose tiles suggest that even a universe based on simple rules can generate infinite, unpredictable complexity. Nature will always present us with new riddles to solve, if we keep our eyes open.

DAVID DEUTSCH AND THE BEGINNING OF INFINITY

David Deutsch opens his 2011 book *The Beginning of Infinity* by asking: “Must progress come to an end—either in catastrophe or in some sort of completion—or is it unbounded?” Deutsch’s book is one long argument for unboundedness. (See my review of Deutsch’s book here and my

conversations with him here and here.)

Deutsch asserts that all our progress—moral, political, technological, medical, artistic, scientific—stems from our attempts to find “good explanations.” There will always be more to explain, Deutsch says, because our knowledge of reality will always be incomplete. Deutsch thus dismisses my claim in *The End of Science* that science might not yield any more insights into nature as profound as evolution, quantum mechanics and the big bang. The discovery of the acceleration of the cosmos, Deutsch argues, contradicts my thesis.

He suggests, moreover, that our descendants might harness the dark energy thought to be fueling this cosmic acceleration so that “knowledge creation” can “continue forever.” Heat death? No problem. Deutsch dislikes all human futures that smack of finality. He thus rejects the possibility of a utopia so perfect that we no longer have problems to solve. He told me in 2018 that “the world will never be perfected, even when everything we think of as problematic today has been eliminated. We shall always be at the beginning of infinity. Never satisfied.”

Deutsch is an adamant advocate of the many-worlds hypothesis, which seeks to explain why, when we observe an electron, we see only

one of the many possible trajectories represented by the electron's wave function. The many-worlds hypothesis holds that all the possibilities embodied by the wave function are realized in other universes. When I interviewed him in 2018, Deutsch likened the evidence for alternative realities to the evidence for dinosaurs. Other universes are "real," he said. "Get over it."

I recently asked Deutsch ask if he thought our descendants might be able to jump to other universes to continue knowledge seeking. In his response, Deutsch showed that his optimism, like that of Dyson and Penrose, is tempered by hard-headed skepticism. Universe jumping might be possible under certain "exotic and highly speculative scenarios," Deutsch said.

"But future generations might think it a little comical," he added, "for us to be speculating about events 100-plus billion years in the future when our theories of basic cosmology are still changing on a timescale of decades. A bit like someone in 1400 speculating about the future domestication of fire-breathing dragons for steelmaking because their maps speculatively said 'here be dragons' on unexplored regions."

Yes, the prophecies of Dyson, Penrose and Deutsch contradict my claim that science is finite. But we share convictions, too, namely, that we will never entirely solve the riddle of reality and that knowledge seeking, more than any other endeavor, makes our existence meaningful. Moreover, the older I get, the more my hope that science is infinite outweighs my fear that it's not. I guess I have faith in progress after all.

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John Gertz is president of the Foundation for Investing in Research on SETI Science and Technology and former chair of the board of the SETI Institute. He is also president and CEO of Zorro Productions, a multimedia entertainment company.

SPACE

Maybe the Aliens Really Are Here

But if so, it's probably in the form of robotic probes—something both UFO enthusiasts and SETI scientists should be able to agree on

SETI, as a modern astronomical endeavor, dating to 1959 ([first paper](#)) and 1960 ([first observation](#)). Modern UFO sightings date to the late 1940s. Though superficially similar, the two fields in practice have had virtually nothing to do with one another. SETI usually requires a graduate degree in astronomy, and its scientists tend to disdain UFOers for requiring nothing more than a camera that takes blurry photos and a butterfly net in case a little green man appears.

Now the two camps may be moving closer together.

In the classic SETI paradigm, stars are observed for artificial signals. But this communication strategy has severe drawbacks from ET's point of view. In order for it to succeed, ET would have to target each of potentially millions of promising nearby stars (including ours) continuously and do so over potentially billions of years.



Additionally, it would need to maintain a dedicated receiver for each target star to be certain not to miss a return message if and when it arrives. The cost of this strategy to ET in time, energy and materials would be immeasurable. Further, by announcing its presence to so many stars, it invites disaster should any civilization prove aggressive. Added to this is the problem of communicating with a target civilization of which it would know nothing. Perhaps the transmitting

civilization communicates in color oscillations like a cuttlefish, while the recipient understands only beelike waggles.

Building on the work of others, I have hypothesized that aliens would be better served by sending robotic probes. Relatively simple flyby probes might intermittently surveil nascent solar systems, for example, at 200-million-year intervals. Star systems with biogenic planets might be surveilled more often. Highly capable probes

might be placed permanently in the vicinity of planets that have achieved multicellularity as indicated by their oxygen-rich atmospheres or other biosignatures.

Once a permanently placed probe had detected artificial electromagnetic leakage, indicating that one multicellular species had become technologically intelligent, it would attempt to decode the species. Using *Sesame Street*, Khan Academy and YouTube, and even granted its enormous onboard AI capabilities, it would still take time for it to decode *Homo sapiens'* languages, science, math and culture. After many decades of work by E. O. Wilson and others, we now know a little something about ant communication but are still far from a complete decoding. How very much more difficult would it be for ET to decode humans? Even if it has been watching episodes of *I Love Lucy* that have been leaking out into space since that show was first broadcast, it may still not understand them.

The local probe might need to send data back to its home base for deeper analysis and/or instructions on how to proceed. If the probe began transmitting data to its home in 1950 after its detection of early television signals and if that home base were located at the modest distance of 150 light-years, then the earliest year in which the probe might receive instructions to make contact with Earth would be 2250.

Yet when we do finally hear from a local probe, after it has decoded us, its transmissions may be in a terrestrial language. The ensuing dialogue will take place in near real time, as opposed to the

painfully slow dialogue between ourselves and an alien civilization transmitting from a star at hundreds or thousands of light-years distance. An alien probe need not reveal the location of its home base, obviating any danger to the progenitor civilization. A fully autonomous probe would be able to communicate with us even if its progenitor civilization is long extinct.

Provided that a probe does belong to an existing civilization or network of civilizations, there remains the problem of how it might communicate with them. To do so directly would require an enormous transmitter. The better solution would be to string communication nodes at close proximity to one another, perhaps one in orbit around every star and perhaps located at a sufficient distance from the star to enable the use of it as a gravity lens, per Einstein's theory of general relativity. For the sun, that focal point begins at 550 Earth-sun distances (AU), at which point the node would achieve a signal gain of approximately one billion.

Large numbers of ET civilization might contribute to this nodal system, and the store of information would only grow with time regardless of whether the contributing civilizations persist or have gone extinct. We might contribute Aristotle, Shakespeare, Beethoven and Monet to this *Encyclopedia Galactica*. But we will not be in a position to barter our culture; having surveilled our TV and Internet for at least 70 years, ET has probably already uploaded all it wants. Nevertheless, ET may wish to recruit us into the galactic club so that we might manufacture probes and nodes and otherwise take responsibility for the

maintenance of the interstellar communication system within our immediate stellar neighborhood. That would be our bargaining chip.

SETI stellar observations presume a very faint signal that would require Earth's most powerful telescopes to detect. Highly sensitive telescopes have very small fields of view, however. Detecting a local robotic probe requires the opposite strategy. Because of a probe's close proximity to Earth, its signal would be much brighter than an interstellar beacon, even under the conservative assumption that its transmission will be on the order of only a few watts. Consequently, SETI's best strategy would be to sacrifice great sensitivity in favor of a wide field of view or, better yet, all-sky-all-the-time observing. Such systems are being built now or planned.

Purported sightings by military pilots of objects that defy all known aerodynamics in their sudden and steep accelerations may be delusions, hoaxes or optical illusions. Nevertheless, many SETI scientists now agree with UFOers that the first alien detection plausibly could occur within our own solar system. Both UFOers and SETI scientists should also agree that if some UFO sightings are genuine sightings of aliens, then they must be of robotic probes rather than vessels crewed by biological beings. If nothing else, such beings would be crushed by the g-forces of their purported, very large, accelerations.

The evidence is still lacking that would fully unify UFOers and SETI scientists—and yet the space between these two groups may not be so vast after all.

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